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PROJECT SQUID

SEMI-ANNUAL PROGRESS REPORT

1 APRIL 1978

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PROJECT SQUID HEADQUARTERS
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PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA

Project SQUID is a cooperative program of basic research relating to Jet Propulsion. It is sponsored by the Office of Naval Research and is administered by Purdue University through Contract N00014-75-C-1143, NR-098-038.

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SEMI-ANNUAL PROGRESS REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM OF FUNDAMENTAL RESEARCH
RELATED TO JET PROPULSION
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

THIS REPORT COVERS THE WORK ACCOMPLISHED
DURING THE PERIOD 1 OCTOBER 1977 TO MARCH 31, 1978
BY PRIME AND SUBCONTRACTORS UNDER
CONTRACT N00014-75-C-1143, NR-098-038

1 APRIL 1978

PROJECT SQUID HEADQUARTERS
CHAFFEE HALL
PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA 47907

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I. AERODYNAMICS AND TURBOMACHINERY

Semi-Annual Progress Report

THREE DIMENSIONAL TRANSONIC FLOWS IN COMPRESSORS AND CHANNELS

The University of Michigan, Ann Arbor, Michigan
Subcontract No. 8960-10

Professor T. C. Adamson, Jr., Principal Investigator
Professor M. Sichel, Principal Investigator

Introduction

The work described here is a study of three dimensional transonic channel flows using asymptotic methods. Consideration of such flows, which arise in transonic cascades, is important because of the possibility of mixed supersonic-subsonic flows where two dimensional solutions are completely inadequate. The analysis has focused on those regimes of flow where asymptotic methods can be used to derive relatively simple analytical solutions to the flow fields. A model flow consisting of a shear flow passing through a three dimensional channel with a flow constriction has been considered. This model problem contains the main features of flow in a cascade, but in a very simple geometry. Asymptotic methods have been used to identify those regions where solutions derived from linearized equations are not uniformly valid, and where, therefore, it becomes necessary to use nonlinear equations. The basic philosophy, has been to develop simple approximate, but analytical, solutions which display the effects of various parameters on the nature of the flow, rather than to attempt a detailed numerical analysis.

Discussion

The model problem chosen for study may be interpreted as the flow through a linear cascade with the blades aligned parallel to the incoming flow. The symmetry boundaries upstream and downstream of the blades are replaced by walls so that the flow considered is that through a rectangular channel with flow constrictions corresponding to half blades on opposite walls. The radial variation of the rotor tangential velocity component is represented by a linear gradient of the velocity entering the channel. Because of this gradient, a portion of the incoming flow may be subsonic and a portion supersonic, and this is the type of flow which has been considered.

The nature of this model flow will depend on the location of the sonic surface of the incoming shear flow with respect to the channel, the thickness ratio of the flow constrictions used to represent the turbine blades, and the velocity gradient of the incoming shear flow. The essential features of such flows in the absence of shock waves are described in references 1 and 2. Key results are the verification that linearized equations can be used to describe most of the flow and the establishment of conditions under which choking occurs. In addition, the inner regions at the blade leading edges, where weak shocks may occur, and at the plane of minimum crosssectional area, where singularities in the solution may occur, have been investigated. These results are described in references 1 and 2.

Shock waves may appear when a flow with a subsonic average Mach number at the inlet accelerates until an average supersonic Mach number is attained downstream of the section of minimum area. The detailed study of such shock waves has been continued during the period covered by this progress report. If the flow accelerates to a slightly supersonic average Mach number, the

shock wave which may appear will not fill the channel because of the gradient in the incoming flow. This feature makes the analysis of such shocks more complicated than in the simpler case of one dimensional channel flow.

As established earlier, most of the flow field can be described by linear equations; but, very close to the shock wave, the nonlinear transonic small disturbance equations are required. In order to understand the main general features of the flow, the method of integral relations is being used to develop simple approximate solutions. Preliminary results, which have been obtained so far, show that if the sonic line reaches a position such that 90% of the channel flow is supersonic just ahead of the shock, then the shock extends about 75% of the distance across the channel. On the other hand, the shock extends only about 32% of the distance across the channel when 70% of the mainstream flow is supersonic. The detailed analysis leading to these results have revealed the complexity of such flows, particularly with respect to the region of upstream influence of the flow downstream of the shock.

As already mentioned, there is a region near the leading edge of the blades where the linear equations used in most of the flow are invalid. The flow in this region has been studied in detail during the current contract period and it has been possible to show that local solutions at the leading edge match asymptotically with the first order solutions, used in the earlier analysis, which are valid away from the edge.

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AXIAL FLOW FAN STAGE UNSTEADY PERFORMANCE

Applied Research Laboratory
The Pennsylvania State University
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Subcontract No. 8960-4

Edgar P. Bruce, Principal Investigator

Introduction

The objective of this research is to analyze the time-dependent interaction between the components of an isolated axial flow fan stage and a spatially fixed, circumferentially varying flow field. The major variables are reduced frequency; rotor blade space-to-chord ratio, stagger angle, mean angle of attack, and design loading level; and rotor-stator axial spacing.

The experiments are being conducted in the ARL Axial Flow Research Fan. This facility has a hub radius of 12.06 cm (4.75 inches), a hub-to-tip radius ratio of 0.442, and operates in the subsonic incompressible flow regime. The rotor and stator blades have a 10 percent thick C1 profile with a chord of 15.24 cm (6.00 inches) and an aspect ratio of unity.

Instrumentation available at present or under development consists of: (1) a strain gaged sensor mounted within one rotor blade which detects the time-dependent normal force and pitching moment developed on a mid-span blade segment, (2) hot-film sensors mounted on the suction surface of rotor and stator blades which detect the nature of the boundary layer, i.e., whether the instantaneous boundary layer flow is laminar, turbulent or separated; (3) dynamic total head probes; (4) two-element hot-film probes; and (5) conventional three-dimensional directional probes. A system is being developed which will permit on-line analysis of all time-dependent signals by a digitizing, phase-lock averaging process.

The unsteady normal force and pitching moment results obtained in the initial phase of this program at reduced frequencies from 0.2 to 2.1 have been documented in a Project SQUID report (Reference 1). Since completing the initial phase, our efforts have been directed toward extending the reduced frequency range of the uncambered rotor experiments (Reference 1) from 2.1 to 5.0, and toward a detailed examination of the effects of inflow distortion on the performance of a stage designed with a free-vortex loading distribution. A related theoretical effort has as its goal an extension of the unsteady lift cascade model developed by Henderson (Reference 2) to include the unsteady pitching moment.

Discussion

During this reporting period, we have made significant progress in both the experimental and theoretical areas. With respect to the experimental tasks, we have:

1) completed through final data reduction a thorough recalibration of all the disturbance generating screens used to produce multicycle rotor inlet axial velocity profiles,

2) measured, using 5-hole probes located immediately upstream of and approximately one-half chord length downstream of the free-vortex loading distribution rotor, the circumferential variation of the time mean inlet and exit flow properties at mean incidence angles of zero and seven degrees with different disturbance generating screens installed to give a reduced frequency range from 0 to 5.0, and

3) completed static and dynamic calibration of the sensors required for the unsteady force and moment testing of; a) the free-vortex loading distribution rotor at reduced frequencies from 0 to 5.0, and b) the uncambered rotor at reduced frequencies from 2.1 to 5.0.

Data from the testing outlined under 2) above are being reduced at present. Preliminary results indicate that a reduced frequency range exists for which an incoming sinusoidal distortion in axial velocity component/total pressure is attenuated to approximately one-tenth of its upstream level. On either side of this reduced frequency range, the corresponding flow properties are attenuated to approximately forty percent of their upstream levels. The testing outlined under 3a) above will be initiated in March 1978 and will be immediately followed by the testing outlined under 3b).

An independent derivation of the expression developed by Henderson (Reference 2) for the unsteady lift generated on the blades of a cascade due to operation in a distorted inflow has been completed as a prelude to extension of this model to include an expression for the unsteady pitching moment. The results of the present derivation, in general, agree with Henderson's results; however, errors have been found and corrected in the following areas:

1) the combination of values of the cascade parameters space-to-chord ratio (S/C) and stagger angle (ξ) for which the results are valid,

2) the derivation of one of the two terms which define the effect on the unsteady lift on the reference blade ($n = 0$) due to all the neighboring blades ($- \infty \leq n \leq - 1$) and $1 \leq n \leq \infty$), and

3) the type of camber line for which the solution is valid.

The effect of the change under item 1) above is to include certain values of (S/C) that were previously excluded for values of sin $\xi < 0.25$ and to exclude certain values of (S/C) that were previously included for values of sin $\xi > 0.25$. A preliminary evaluation of the effect on predicted unsteady lift due to the change noted under item 2) above indicates that the effect is small. With regard to item 3) above, the camber line shape employed in Reference 2 is a symmetrical parabolic arc -- not a circular arc.

The unsteady moment expression has been derived to the point where the expression for the symmetrical parabolic arc camber line shape and the flow tangency boundary condition are being included. After simplifying the resulting expression as much as is possible, it will be programmed for solution on the IBM 360 computer.

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INVESTIGATION OF THE EFFECTS OF HIGH AERODYNAMIC LOADING ON A CASCADE OF OSCILLATING AIRFOILS

United Technologies Research Center
East Hartford, Connecticut 06108
Subcontract 8960-19

Franklin O. Carta, Principal Investigator
Arthur O. St. Hilaire, Principal Investigator

Introduction

The basic objective of this research program is to study the phenomenon of dynamic stall on a cascade of oscillating airfoils. Measurements are being made of the unsteady chordwise pressure distribution, and efforts are being made to detect the occurrence of boundary layer transition and separation on the surface of an oscillating cascaded airfoil operating near the static stall condition.

Program Review

Tests completed at a mean incidence angle of 6° continue to show the strong influence of interblade phase angle on blade aerodynamic response. This is based on oscilloscope observations made during the test; however, it is evident that the stall breakdown of the pressure signal near the leading edge is altered

radically as interblade phase angle is changed from positive to negative values.

In addition to blade unsteady pressures, measurements are also being made of the unsteady sidewall pressures in the plane of the cascade. Strong oscillatory signals have been observed in both leading and trailing edge regions. These data are needed to assist in the formulation of an analytical model for unsteady flows past heavily loaded cascades, which is the basis of our planned future work.

Upon completion of our current test at 10° incidence, the system will be prepared for our phase II work which consists of selecting a specific mean incidence angle, testing at several gap/chord ratios, and reducing all of the data.

INVESTIGATION OF ADVERSE PRESSURE GRADIENT CORNER FLOWS

University of Washington, Seattle, Washington
Subcontract No. 8960-27

Professor F. B. Gessner, Principal Investigator
Mr. S. Ono, Research Assistant

Introduction

This program is a comprehensive experimental study of turbulent flow along a streamwise corner in the presence of an adverse pressure gradient. Under these conditions it is known that secondary flows appear in the vicinity of the corner and are amplified as the flow decelerates [1]. For moderate adverse pressure gradient (non-separating) flow conditions, secondary flow velocities are approximately 10 per cent of the primary flow component, which is an order of magnitude greater than that which has been observed in favorable and zero pressure gradient corner flows. For conditions near incipient separation, it is probable that the 10 per cent figure noted above will be exceeded, especially in the vicinity of a corner where the flow first separates locally from the wall.

In order to make measurements in an environment where the mean flow direction varies from point to point in the flow, one must decide whether to align probes with the local mean flow direction or account for cross-flow effects using probes aligned with the streamwise flow component. The latter method of measurement was chosen in the present study, primarily because of probe alignment difficulties associated with the former method. In order to make accurate measurements in a skewed mean flow, hot-wire probe configurations must be selected which minimize distortion of flow in the vicinity of the sensing element induced by flow over the supports. The pitch and yaw angles of the wire relative to the local mean flow direction must also be such that cross-flow induced tangential cooling effects can be readily modelled. In the present study a single "normal" wire

probe (α= 0°) and a rotatable inclined wire probe (α= 45°) were selected in lieu of an X array or a multi-wire configuration to minimize drift problems and resolution inaccuracies.*

Discussion

For the past six months we have been engaged in an extensive experimental program designed to provide information on response behavior of hot-wires in a skewed mean flow. The extent of this work exceeded our original expectations, but has proven to be well-worthwhile from the standpoint of providing vital information needed to make accurate mean-flow and turbulence measurements in this environment. In general, the mean bridge voltage output from a hot-wire anemometer, E_b, may be expressed as

$$E_b^2 = E_o^2 + BU_e^n \tag{1}$$

or, alternatively, as

$$E_b^2 = E_o^2 + BU_e^{0.5} + CU_e \tag{2}$$

where U_e is the effective cooling velocity across the wire, n is an exponent which varies typically from 0.4 and 0.5, B and C are coefficients which are constant for constant temperature operation of the wire, and E_o^2 is the intercept of a least-squares-fit of the data when plotted either as E_b^2 vs U_e^n or as E_b^2 vs $U_e^{0.5}$. The effective cooling velocity can be modelled in terms of the local mean velocity component in a given plane, U_o, the angle between U_o and the normal to a wire in that plane, ψ, and a tangential cooling factor, k, as follows:

$$U_e = U_o(\cos^2 \psi + k^2 \sin^2 \psi)^{\frac{1}{2}} \tag{3}$$

For turbulence measurements with inclined wires it is imperative that the factor k be determined accurately for each local operating condition, inasmuch as turbulent shear stress components are sensitive to the ratio $(1 + k^2)/(1-k^2)$

*The angle α is defined as the angle between the streamwise component of the local mean velocity in a given plane and the normal to a wire in that plane.

and transverse normal stress components are sensitive to $(1+k^2)^2/(1-k^2)^2$ when $\alpha = 45°$ [2]. In applications where an inclined wire is oriented to $\psi = \alpha = 45°$ (no cross flow), it is permissable to assume that $k = k(\ell/d)$ only over a restricted range of values for U_o, where ℓ/d is the wire length-to-diameter ratio [3]. When the mean flow is skewed, however, k is also dependent on ψ, so that $k = k(\ell/d, \psi)$ [4]. These variations of k with ψ are not small, and can lead to a 2:1 change in k values as ψ varies from 15 to 75 degrees. In References 3 and 4 only relatively narrow ranges of velocity were considered, and a constant value of n(0.45) was assumed to be adequate for correlating the data in each velocity range.

In our work we have examined the scope of applicability of these correlations over a relatively wide range of flow conditions ($1 \leq U_o \leq 30$ mps, $15 \leq \psi \leq 75°$). This work entailed modification of our jet flow calibration facility by the addition of a viewing microscope and turntable. With these modifications wire inclination angles could be set with precision to within ±0.25 degrees. Our turbulent pipe flow calibration facility was also modified by adding a traversing and rotating mechanism at the pipe discharge. This modification enabled us to simulate a skewed mean flow across a wire by inclining the probe in fixed degree increments from the axial flow direction.

With 5 μ diameter tungsten wire probes located in the potential core of a free jet ($170 \leq \ell/d \leq 233$), the mean bridge voltage was measured for various combinations of U_o and ψ. A least-squares-fit was applied to the data and k was evaluated by means of either equation (1) or equation (2) in combination with equation (3). The results indicate that when equations (1) and (3) are utilized, $k(\psi)$ is a uniquely specified function, provided that the variation of n with U_o is prescribed properly. The exponent n varies typically from $n \simeq 0.48$ at $U_o = 3$ mps to $n \simeq 0.40$ when $U_o = 30$ mps. These results have important implications because they demonstrate that indiscriminate use of the $k(\ell/d)$ correlation presented by Champagne et al.[3] and the $k(\ell/d, \psi)$ correlation developed by Friehe and Schwarz [4] will lead to significant errors in estimated values for k unless n is allowed to vary with U_o, even when no cross flow exists.

The adequacy of the correlations for $k(\ell/d, \psi)$ and $n(U_o)$ which have been developed in the present study have been tested by means of measurements with a rotatable inclined wire probe in the potential core of a free jet. The results indicate that pitch and yaw angles as large as 30 degrees can be measured to within an accuracy of ±1 degree when the prescribed correlations are used. If a mean (constant) value for k is specified, pitch and yaw angles are overestimated

by as much as 5 degrees. In order to analyze the response sensitivity of hot-wires to turbulent fluctuations in a skewed mean flow, response equations (second-order accurate) have been developed which account for tangential cooling effects induced by a transverse mean flow. The range of validity of these equations was examined by making Reynolds stress measurements in fully developed turbulent pipe flow with "normal" and inclined wires oriented at yaw angles of 10, 20, and 30 degrees relative to the axial mean flow direction. The measurements were made over a radial interval $0.1 \leq r/R \leq 1.0$ at bulk flow Reynolds numbers of 20,000 and 150,000 for which $n \simeq 0.48$ and $n \simeq 0.40$, respectively. The results show that first-order theory begins to break down when yaw angles exceed 10 degrees, and that second-order theory is accurate for yaw angles as high as 30 degrees, provided that $k(\ell/d, \psi)$ and $n(U_0)$ are specified in accordance with the correlations which have been developed. This phase of the work will be written up shortly in the form of a Project SQUID Technical Report.

The above study has delayed somewhat the initiation of measurements in our rectangular diffuser facility for the purpose of investigating adverse pressure gradient effects on flow in the corner region. We feel justified in pursuing our response sensitivity study, however, because: (1) the work is of fundamental importance, and (2) the information gleaned from this phase of the work will assist us in analyzing data obtained in our corner flow work.

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SQUID PR-3

TRANSITORY STALL IN DIFFUSERS

Thermosciences Division
Department of Mechanical Engineering
Stanford University
Stanford, California 94305
Subcontract No. 8960-24

Professor James P. Johnston, Principal Investigator
Professor Stephen J. Kline, Principal Investigator
Mr. Jalal Ashjaee, Research Assistant
Mr. John Eaton, Research Assistant

Introduction

The general goal of this program is to study the transitory stall flow regime in two-dimensional diffusers. Maximum value of pressure recovery at fixed non-dimensional length, an important design optimum [1], generally occurs when the turbulent boundary layers are starting to separate or stall. The flow is rather unsteady and significant amounts of transient back flow already are seen in the diffuser at peak pressure recovery. These flow conditions are associated with the onset and development of the transitory stall flow regime [2].

Ghose and Kline [3] have developed a new, steady flow boundary layer prediction method which is solved simultaneously (not iteratively) with the inviscid core flow. This method gives surprisingly good agreement with data on pressure recovery up to, and slightly beyond the condition of peak recovery. The existing wall pressure data in this region are not of sufficient accuracy to properly check the method, however.

The primary objectives of our program are (i) to provide new mean and fluctuation velocity and pressure data in diffusers operating close to peak pressure recovery in order to complement, check and provide a data base of sufficient accuracy to allow for possible improvement of the prediction method of Ghose and Kline [3], and (ii) to study the magnitude of the velocity and pressure fluctuations in the transitory stall regime in order to provide a useful extension of the work of Smith and Kline [2] and Layne and Smith [4].

Discussion

Work is proceeding in several areas, (i) the collection and correlation of wall static pressure distributions and inlet velocity profiles, and (ii) the development of a new wall flow direction instrument.

The diffuser tunnel is now complete except for the heat exchanger and associated control components. It has been checked out and is now being used to collect the mean flow data.

Diffuser Experiments are now in progress with the objective of obtaining accurate, detailed static pressure distributions in a long ($N/W_1 = 15$) , straight-walled diffuser for a set of opening angles, 2θ . Fig. 1 in the progress report of March 15, 1977, shows the general configuration for this first series of tests. The diffuser inlet width is $W_1 = 3.00$ inches and the distance between parallel walls is $b = 12.00$ inches so the inlet aspect ratio is 4:1 .

Fig. 1, below, shows some details of the inlet configuration. The 13.4 inch long inlet duct, with its boundary layer trips, assures the development of identical turbulent boundary layers on all four diffuser walls at the inlet station located a distance $S/W_1 = -1.15$ with respect to the diffuser throat.

For the current series of tests, the measured inlet conditions are:

Air Pressure: 1 atmosphere
Air Temperature: 84°F
Kinematic Viscosity: 1.7×10^{-4} ft^2/s
Free Stream Speed: $U_{e1} = 151$ ft/s
Reynolds Number: $W_1 U_{e1}/\nu = 2.2 \times 10^5$
Boundary Layer Parameters (Preliminary):

δ (99%) = 0.33 inches
$\delta^* = 0.041$ inches
$\theta = 0.032$ inches
$H = 1.3$

The overall static pressure recovery coefficients, $Cp_{TOT} = (p_1 - p_2)/\frac{1}{2}\rho U_{e1}^2$, are given below. The inlet state (1) is defined at the inlet station denoted on Fig. 1. The exit station (2) is located in the short, constant area tailpipe, 3 inches downstream of the diffuser. Experimental uncertainties for the overall recovery coefficients are yet to be determined, but we hope to achieve uncertainties as low as $\pm$ 1 to 2% (20:1 odds).

2θ (degrees)	Cp_{TOT}	Remarks
0	---	Test to establish inlet pressure drop
4	---	Unstalled case
8	.714	Early transitory stall
10	---	Close to peak Cp_{TOT}
12	.655	Transitory stall
16	.610	Transitory stall with large fluctuations
20	.538	Transitory stall with large fluctuations
24	---	Transitory stall with large fluctuations

The detailed, local wall static pressure distribution for the results obtained to date are shown in Fig. 2. Work is in progress to complete the results at 2θ = 0, 4, 10 and 24 degrees.

Prediction of the pressure recovery distributions using the UIM method [2] will be accomplished shortly.

Measurement Techniques. Both channels of pulsed wire anemometry and probes were delivered, and preliminary experiments to check their operating characteristics have commenced. These instruments were purchased at no cost to the project.

A wall-flow direction indicator has been developed in our laboratory. The probe holds three fine wires, 0.25 inches long, that are mounted parallel to each other at a spacing of 0.1 inch. The probe plug fits flush into the wall of a flow channel so that the wires are held perpendicular to the through flow direction. The two outer wires are set out from the wall about 1 mm on short prongs and the center wire is set in a shallow groove. The center wire is driven with a steady current so that it produces a hot wake which is swept downstream, or upstream, over one of the outer wires. The outer wires, operated as resistance thermometers, detect the wake and, by use of a simple comparator circuit, give the instantaneous sign of the fluid velocity in a thin layer near the wall. The system has been successfully tested in a reattaching turbulent shear flow, and will be applied for the detection of the unsteady flow separation points in our diffuser experiments.

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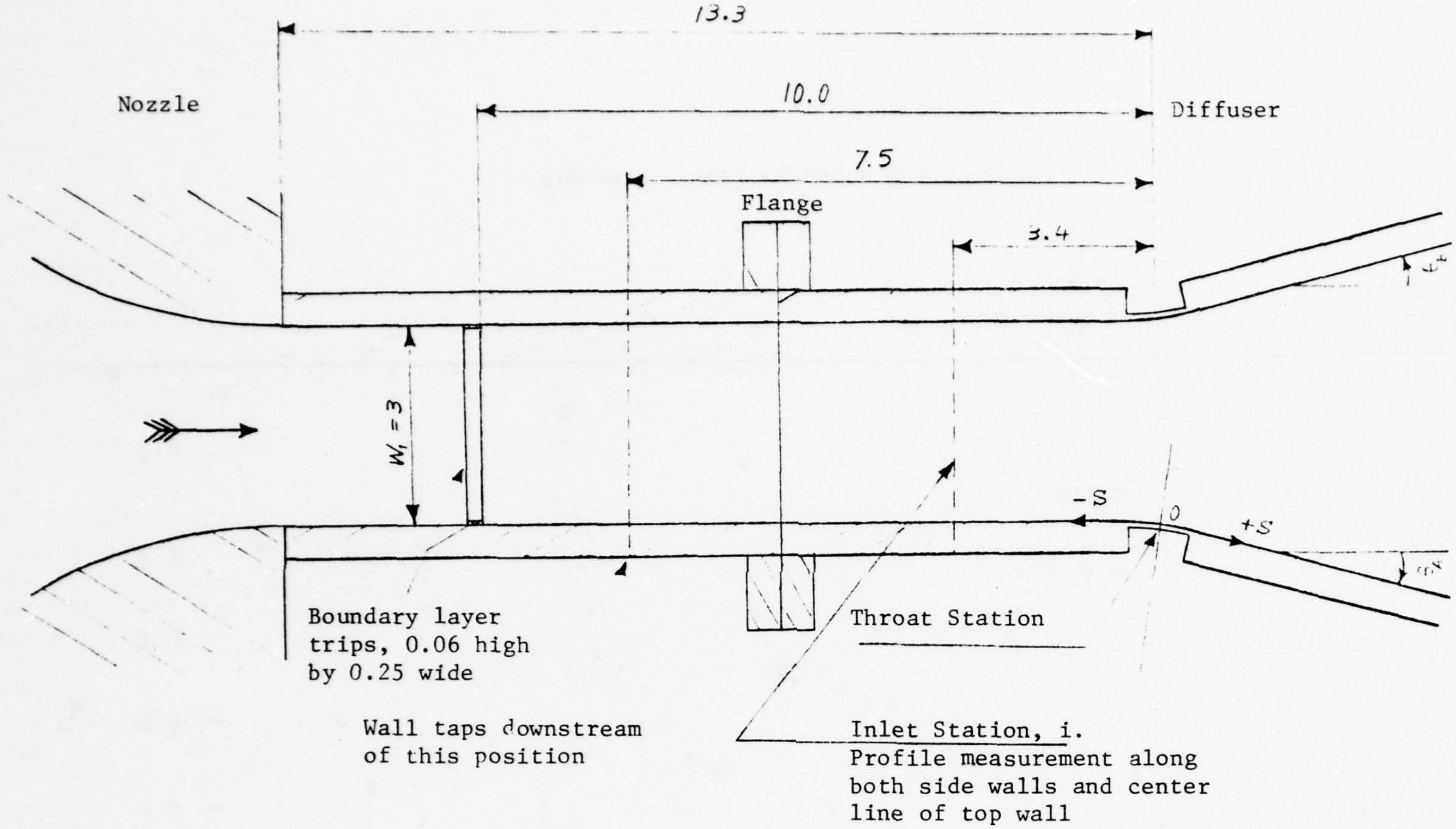

Figure 1 - Inlet Geometry

(Parallel Walls 12 Inches Apart.) All Dimensions in Inches.

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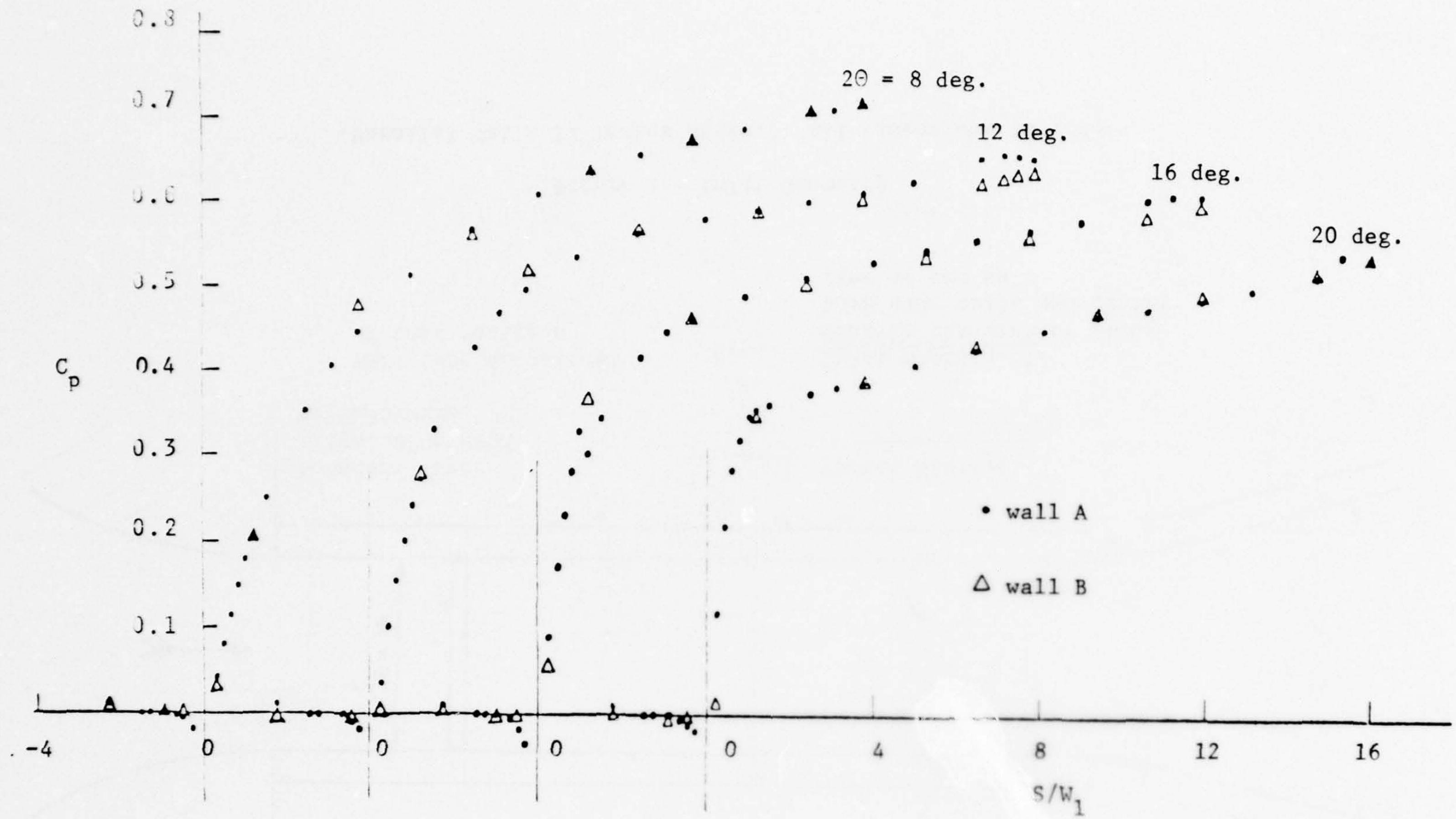

Figure 2 - Wall Pressure Coefficient

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AN INVESTIGATION OF PRESSURE FLUCTUATIONS AND STALLING CHARACTERISTICS ON ROTATING AXIAL-FLOW COMPRESSOR BLADES

Virginia Polytechnic Institute
and State University, Blacksburg, Virginia
Subcontract No. 8960-13

Professor H. L. Moses, Principal Investigator
Professor W. F. O'Brien, Jr., Principal Investigator
Mr. R. R. Jones, Research Assistant
Mr. W. F. Siedlecki, Research Assistant

Introduction

The overall goal of this research program is to provide a better understanding of stall-related phenomena in axial-flow compressors. The aspects of compressor performance that are of interest include the onset of stall, loss in performance, and the flow instabilities associated with stall.

The program involves both experimental and analytical efforts. A primary feature of the experimental work is the measurement of pressures directly on the rotor of test compressors, for flow conditions up to and including stall. For high-frequency-response measurements, special radio telemetry data transmission equipment has been developed for use with blade-mounted transducers. Average and slowly-varying pressure measurements are made employing a pressure scanner that has been adapted to rotate with the compressor rotor. Ports on the compressor blades are connected by tubing to the scanning valve. Pressure measurements are made by a single transducer located at the shaft center.

Experimental work is conducted employing a low-speed, single stage research compressor operating at approximately 2400 rpm, and a recently-completed high-speed drive facility. A three-stage research compressor designed for operation in the 13000-17000 rpm range is presently being readied for use in this facility.

During the present reporting period, the use of high response dynamic pressure probes to supplement on-rotor pressure measurements was investigated. Two probes were installed downstream of the rotor of the low-speed test compressor, and measurements were made with rotating stall present. Work is proceeding to install similar probes in the first-stage stator row of the high-speed test compressor. This test compressor is being prepared for a series of experiments to determine the stall point of the rotor blades, and to compare the observed behavior with predictions of a separated-flow theory which has been devised. Progress was made in the development of this theory, and in several areas related to the initial operation of the high-speed research compressor.

Discussion

Development of techniques for on-rotor pressure measurements in low-speed axial-flow compressors has been previously reported in connection with the present program. In order to study the time-response of the rotor blades to disturbances which produce stall, it is necessary to provide for high-frequency-response pressure measurements in the stationary components of the compressor as well.

Two dynamic pressure probes (KULITE XCQH-152-15D) were installed in the single-stage low-speed research compressor at 120° circumferential separation, and on traverses which permitted radial movement. The probes were located approximately 15 mm behind the rotor of the compressor. The probes proved very effective for indicating the presence of rotating stall, and for measuring the radial and circumferential extent of the cells [1]. Preparations are underway for similar high-response flow measurements downstream of the first-stage rotor of the high speed research compressor. Primary considerations involve the method of mounting and radially traversing the probes, and the flow blockage effects of the probes when mounted within the first-stage stator now. The high-response probes will be used to determine the type of unstable behavior which occurs in the rotor, and to measure the rate of flow fluctuations. A related experimental effort planned for the high-speed facility is directed at determining the mean flow performance of the research compressor up to stall, for comparison with the basic analytical model.

Recent progress in both efforts includes completion of a new test rotor, final design of the inlet and exit ducting, design of the first experimental program, and selection of the necessary instrumentation. The test compressor has been prepared in a three-stage configuration with new bearings, balanced, and is now ready for installation in the facility. The inlet and exit ducting, which includes a variable volume discharge plenum and quick-release valve, has been designed and is presently under construction. The first experiments will include flow measurements at the compressor inlet, after the first-stage rotor, after the last (third) stage, and in the plenum. An automatic traversing mechanism will position the measurement probe behind the first-stage rotor.

The analytical effort is directed toward developing a basic model for predicting stall in axial-flow compressors which can be compared with the experiments. Recent progress in this aspect of the program includes a basic procedure for calculating separated boundary layers, a prediction method for turbulent boundary layers with separated flow, a computer program for radial equilibrium, and a blade-to-blade program for the compressible, inviscid flow. The procedure for calculating separated flow [2] involves a simultaneous solution of the boundary layer and freestream at each longitudinal position. The solution begins at the upstream boundary and iterates over the flow field to satisfy the elliptic nature of the freestream equation. Stability and convergence of the basic procedure were first demonstrated with laminar, internal flow.

The turbulent boundary layer prediction method is an integral method that can be easily used with the above separated flow procedure. The method employs the momentum and kinetic energy integral equations and, except for the

extension to separated flow, is not greatly different from a number of previous methods. The velocity profiles are made up of the usual logarithmic and wake functions, but in the separated region the wake function does not extend to the wall. Thus in the limit, the profiles result in a free shear layer at a large distance from the wall, similar to the Stewartson profiles for laminar flow. The dissipation integral is being determined from available experimental results, which are quite limited for separated flow.

The radial equilibrium program is a straight-forward calculation that can be used with the blade-to-blade program to calculate the full blade passage. Streamline shift is determined from simple radial equilibrium, and the axial shape of the stream sheets, which are assumed axially symmetric, is approximated by Horlock's experimental function.

The blade-to-blade program has been completed for compressible, inviscid flow and is similar to the Katsanis program. However, the present computer program, which employs line-overrelaxation, has been developed specifically to incorporate a simultaneous boundary layer calculation that includes separated flow.

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Semi-Annual Progress Report

EFFECT OF TURBULENCE ON FLOW THROUGH AN AXIAL COMPRESSOR BLADE CASCADE

Colorado State University
Fort Collins, Colorado 80523
Subcontract No. 8960-15

Professor Willy Z. Sadeh, Principal Investigator
Mr. Herbert J. Brauer, Research Assistant

Introduction

The long-term objective of this research program is to ascertain the role which oncoming turbulence plays in reducing the aerodynamic losses in flow through a blade cascade of an axial-flow compressor at moderate Reynolds numbers of order of $2x10^5$ or smaller. At these Reynolds numbers prohibitively high losses and even fully stalled blades are induced by laminar separation of the profile boundary layer. Supply of oncoming turbulence of sufficient energy concentrated at scales commensurate with the thickness of the prevalent profile boundary layer can forestall the laminar separation. Suitable management of the turbulent energy distribution possesses further the potential to even generate and sustain a fully attached turbulent boundary layer on the profile suction side. Accumulation of turbulent energy at desired scales can be produced by selective amplification of turbulence. This selective turbulent energy intensification is governed by the vortex-stretching mechanism characteristic to forward stagnation flow.

The research program is divided into three phases of increasing complexity for the sake of ensuring its methodical and successful completion. In all these three phases the evolution of the oncoming turbulent energy, its selective amplification and its effects on the body boundary layer are to be investigated. The bodies to be utilized are: (1) a circular cylinder in the first phase; (2) an isolated airfoil in the second phase; and, (3) a stationary blade cascade in the last phase. Essentially, the first phase represents a diagnostic study regarding the flow features of interest and the foundations for putting forward an adequate theoretical model.

Discussion

The current research efforts concentrate on investigating the oncoming turbulence evolution and the effects of the amplified turbulence upon the flow about a circular cylinder, i.e., the first phase of the research program. An extensive visualization study of the flow near the stagnation zone of a circular cylinder was conducted and completed. The results of this visualization investigation are reported in a Project SQUID technical report [1] which was published recently. A summary movie titled "Vorticity Amplification in Stagnation Flow" which incorporates the most instructive views of the flow was further produced.

The visualization supplied an in-depth qualitative apperception of the flow. A frame by frame scrutiny of selected movie strips led further to the acquisition of a reasonable quantitative interpretation of the gross flow structure. Essentially, the visualization study provided significant and explicit evidence concerning: (1) the selective stretching of cross-vortex tubes; (2) the streamwise biased tilting of stretched cross-vortex tubes; (3) the existence of a coherent vortex flow structure near the stagnation zone; (4) the interaction of the amplified turbulence with the cylinder laminar boundary layer; and, (5) the fostering and growth of a turbulent boundary layer. The visualization revealed clearly that the cross-vortex tubes conveyed by the diverging stagnation flow constitute an organized substructure within the overall turbulent field which is triggered to its fullest manifestation by the stretching mechanism.

The effect of the amplified turbulence upon the position of the separation line was further visualized. By and large, it was found that the separation line can be adjusted within a range of 7 to beyond 10 cm (3 to 4 in) along the cylinder circumference depending upon the characteristics of the oncoming turbulence. A short report describing the results of this endeavor is currently being prepared.

A first survey of the turbulence evolution along the stagnation streamline, i.e., along the x_2-axis, was carried out by means of a single hot-wire anemometer. Measurements were performed at six Reynolds numbers, viz., at $Re_D = 5x10^4$, $7x10^4$, $9x10^4$, $1.2x10^5$, $1.6x10^5$ and $2x10^5$, where Re_D is the cylinder Reynolds number based on the freestream velocity and the cylinder diameter. At each Reynolds number the measurements were conducted at 21 stations ranging from 14 radii upstream of the cylinder up to 0.01 radii close to the cylinder. The surveys were carried out with a turbulence-generating grid made up of vertical rods [1] installed 14.64 radii upwind of the cylinder. During this first survey the streamwise turbulent velocity (rms), i.e., the u_2-component, and its power spectral density function were measured on line. In addition, the data was recorded on FM magnetic tape. The reduction and analysis of the amassed data is currently being conducted. A preliminary analysis of the data clearly revealed that the turbulent energy undergoes manifold amplification close to the body at scales larger than the neutral one. Amplification ratios greater than even 100 times were obtained near the outer edge of the theoretical laminar boundary layer.

The construction of a single NACA 65-010 airfoil was completed. This airfoil has a chord of 122 cm (48 in). Along its circumference 120 pressure taps were drilled. This airfoil will be utilized during the second phase of this research program.

Further efforts regarding the matching of the inner and outer solutions of the vorticity amplification theory have been pursued. Numerical schemes for carrying out the matching by means of a composite asymptotic expansion are being evaluated. An analysis of the differences and the similarities between the rapid distortion theory and the vorticity amplification theory has been initiated. The main objective of this analysis is the ascertainment of the effect of the turbulent velocity gradient upon the stretching of cross-vortex tubes. An additional aim is the examination of the role of viscous dissipation with regard to the stretching mechanism.

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FUNDAMENTAL RESEARCH ON ADVERSE PRESSURE GRADIENT INDUCED TURBULENT BOUNDARY LAYER SEPARATION

Southern Methodist University, Dallas, Texas
Subcontract No. 8960-25

Professor Roger L. Simpson, Principal Investigator
Mr. E. B. Bowles, Research Assistant
Mr. G. P. Kokolis, Research Assistant

Introduction

The problem of turbulent boundary layer separation due to an adverse pressure gradient is an important factor in the design of many devices such as jet engines, rocket nozzles, airfoils and helicopter blades, and the design of fluidic logic systems. Until the last three years little quantitative experimental information was available on the flow structure downstream of separation because of the lack of proper instrumentation.

In 1974 after several years of development, a one velocity component directionally-sensitive laser anemometer system was used to reveal some new features of a separating turbulent boundary layer [1]. The directional sensitivity of the laser anemometer system was necessary since the magnitude and direction of the flow must be known when the flow moves in different directions at different instants in time [2]. In addition to much turbulence structure information, it was determined (1) that the law-of-the-wall velocity profile is apparently valid up to the beginning of intermittent separation; (2) that the location of the beginning of intermittent separation or the upstreammost location where separation occurs intermittently is located close to where the free-stream pressure gradient begins to rapidly decrease; (3) that the normal stress terms of the momentum and turbulence kinetic energy equations are important near separation; and (4) that the separated flowfield shows some similarity of the streamwise velocity U, of the velocity fluctuation u', and of the fraction of time that the flow moves downstream [3].

Based upon these results, modifications [4,5] to the Bradshaw, et al. [6] boundary layer prediction method were made with significant improvements. However, this prediction effort pointed to the need to understand the relationship between the pressure gradient relaxation and the intermittent separation region structure. Another limiting factor for further refinement of the prediction

of separated flows is the lack of fundamental velocity and turbulence structure information, especially in the backflow region. Thus, the objective of the current research program is to provide this information by using a directionally-sensitive laser anemometer system to determine quantitatively the turbulence structure of a separating, separated, and reattached turbulent boundary layer.

Discussion

This current research program was begun October 1, 1976, to obtain laser anemometer measurements of the separating flow of another adverse pressure gradient turbulent boundary layer for an airfoil or cascade blade type pressure distribution. As stated in the last report, considerable effort has been made to avoid mean flow three-dimensionality. Specially designed wall suction and tangential wall jet boundary layer controls and peripheral equipment were installed into the wind tunnel test section. The flow produced by these controls was determined to be two-dimensional within 1%. Recent measurements indicate that the momentum from the specially-designed wall jets persists farther downstream than other more conventional designs. Direct measurements of U and V in the backflow region with the directly-sensitive laser anemometer system have proved that the time-averaged two-dimensional continuity equation is satisfied.

A number of velocity profiles have been measured upstream of separation with a hot-wire anemometer. The streamwise skin-friction behavior is well described by the Ludwieg-Tillmann relation. The mean and streamwise fluctuation velocity profiles agree with previously published results.

Ciné films of laser illuminated smoke have clearly revealed that the large eddy structure supplies most of the near wall backflow. Many measurements of U, V, $\overline{u^2}$, $\overline{v^2}$, $\overline{(U - V)/\sqrt{2}}$, $-\overline{uv}$ the flow reversal intermittency, the skewness and flatness of the velocity probability distributions, and velocity spectra are being obtained in this region with the laser anemometer system. The signal quality of this backscattering system has been considerably upgraded in the last several months. Up to 10^3 data samples per second are being obtained.

Three distinct layers in the backflow have been observed so far. Nearest the wall is a viscous layer that is driven by the large-scaled low frequency unsteadiness of $\overline{u^2}$ and $\overline{v^2}$ of the outer flow. In this layer, $\sqrt{\overline{u^2}}$ is about twice $|U|$. The Reynolds shearing stress $-\overline{uv}$ is immeasurably small, indicating that the mean velocity of this viscous layer is not governed by turbulent momentum transport. It appears that this layer behaves as an unsteady viscous boundary layer that is driven by u and v fluctuations in the second layer.

The normal stresses term $\partial(\overline{u^2} - \overline{v^2})/\partial x$ in the momentum equation and $(\overline{u^2} - \overline{v^2})\,\partial U/\partial x$ in the energy equation [4] are not insignificant in the both the viscous layer nearest the wall and in the second layer. The mean velocity profile for U in the second layer is amazingly flat, i.e., $\partial U/\partial y = 0$, which is in substantial agreement with the near wall measurements of Simpson et al. [3]. $-\overline{uv}$ is also immeasurably small in this layer. It is not surprising then that the mean velocity profile of the viscous layer nearest the wall looks much like a Blasius flat plate laminar layer.

The third and outermost layer of the mean backflow is *really* part of the forward flow of the outer region. The Reynolds stresses are growing and the mean velocity profile is taking on a more mixing layer like behavior.

Further measurements are being made and analytical explanation of this behavior is being pursued.

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II. COMBUSTION AND CHEMICAL KINETICS

A SHOCK TUBE STUDY OF H_2 AND CH_4 OXIDATION WITH N_2O AS OXIDANT

University of Missouri, Columbia, Missouri
Subcontract No. 8960-21

Prof. Anthony M. Dean, Principal Investigator

Introduction

The study of oxidation reactions in shock tubes has been stimulated by the use of fast, accurate numerical integration routines. Now it is possible for kineticists to more definitively test various oxidation mechanisms by a detailed comparison of calculated and observed concentration-time profiles. Although the $H_2/O_2/Ar$ and $H_2/O_2/CO/Ar$ systems have been successfully studied by this approach, extension to even simple hydrocarbon systems like CH_4/O_2 has been limited by lack of reliable high temperature rate constants. A common practice has been to extrapolate low temperature flow system data to the temperature range of interest. Unfortunately this approach can lead to serious errors; recent studies have convincingly demonstrated that many reactions of importance in combustion mechanisms exhibit markedly "non-Arrhenius" rate constants. In this light it appears to be most desirable to measure rate constants in the same high temperature regime where they will be used to test the combustion mechanisms. However, it is equally important that these data be obtained from relatively simple systems where assignment of the desired rate constant is not contingent upon proper assignment of a complex mechanism and the associated rate constants.

One such system results from the substitution of N_2O for O_2 in combustion studies. Recent work in this laboratory [1] showed that N_2O is a particularly useful source of oxygen atoms between 2000-3000 K. Thus, a study of combustion systems where N_2O replaced O_2 should provide useful information about rates of oxygen atom reactions at high temperatures. The primary advantage of N_2O as an oxidant is that oxygen atom reactions will occur in an environment where the concentration of molecular oxygen is much less than a normal combustion system; this considerably simplifies the kinetic analysis. Prudence dictates that such a substitution first be tested on a known system. For this reason our first efforts in the SQUID program utilized hydrogen as the fuel molecule.

The hydrogen work has been completed [2] and suggests the substitution of N_2O for O_2 is a viable method to measure rates of oxygen atom reactions at high temperatures. Furthermore, it appeared that the postulated mechanism for the N_2O system was reasonable. Data were then collected on a variety of N_2O/CH_4 mixtures. Analysis of these data at high temperatures ($T \geqslant 2400$ K) yielded values of the rate constant for $O + CH_4 \rightarrow CH_3 + OH$ in good agreement with recently measured high temperature values. It is significant to note that these values are over five times larger than those obtained by extrapolation of low temperature data; this observation reinforces the thesis that reaction rates used in combustion mechanisms should come from high temperature measurements. Detailed comparisons of calculated and observed profiles at temperatures less than 2200 K indicated unsuspected complexities in the N_2O/CH_4 mechanism. Subsequent experiments suggested that reactions of formaldehyde (CH_2O) were responsible. Thus our efforts have shifted to a study of these reactions.

Discussion

During the last six months, a variety of CH_2O/Ar and CH_2O/N_2O mixtures have been investigated. Particular emphasis has been placed upon the CH_2O/Ar system [3]. Here CH_2O decay was monitored in a series of mixtures where the formaldehyde concentration varied from 0.1% to 1.0%. These data suggest that the reaction is complex, with secondary reactions playing a significant role in the overall disappearance of CH_2O. A possible mechanism is the following:

$$CH_2O + M \rightarrow HCO + H + M \qquad (1)$$

$$CH_2O + H \rightarrow HCO + H_2 \qquad (2)$$

$$HCO + M \rightarrow H + CO + M \qquad (3)$$

$$HCO + H \rightarrow H_2 + CO \qquad (4)$$

At present, we are trying to quantitatively model the decay behavior, as a function of both temperature and concentration, in terms of this mechanism.

Experiments have also been performed in which the formaldehyde decay is measured in CH_2O/N_2O mixtures. As expected, the observed decay rate is enhanced when N_2O is added. The increase is probably due to the fact that the additional reaction channels

$$O + CH_2O \rightarrow HCO + OH$$

$$OH + CH_2O \rightarrow HCO + H_2O$$

are now available. Successful analysis of this system (coupled with earlier work on O-atom production and CO_2 production in $CH_2O/N_2O/CO/Ar$ mixtures) should yield rate constants for these reactions.

When these formaldehyde reactions are characterized, we should then be able to proceed rather quickly in the CH_4/N_2O analysis. Of particular interest here is that the formaldehyde work should be applicable to both the CH_4/N_2O and CH_4/O_2 systems. Thus, the work on CH_4/N_2O should yield detailed mechanistic information directly applicable to practical combustor systems as well as the desired $O + CH_4 \rightarrow CH_3 + OH$ rate constant.

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COMBUSTION KINETICS AND REACTIVE SCATTERING EXPERIMENTS

Yale University, New Haven, Connecticut
Subcontract No. 4965-16

J. B. Fenn, Principal Investigator
B. Halpern and M. Labowsky

Introduction

The combustion of hydrocarbon fuels has been man's most used source of useful energy for much of this century. The chemical reactions which it involves have been among the most studied. And yet, there remains uncertainty as to the nature of the first reactive step in the complex sequence of reactions by which oxygen and hydrocarbon molecules become hot combustion products. This investigation comprises an attempt to identify that first reactive event and to determine its cross section by means of molecular beam scattering methods. The prospective advantage of such methods is that they can examine the consequences of a single collision between individual molecules. By the same token they are substantially limited in their ability to probe intermediate reaction steps which involve species of transient existence such as free radicals not readily obtainable as beams. In addition to this new venture in combustion kinetics we have been continuing a study of the evaporation and combustion of arrays of droplets. This study is based on an adaptation of the method of images which has been successful in solving Laplace's equation as it applies to electrostatic problems involving arrays of charged particles.

A. Reactive Scattering. The objective is to identify and measure cross sections for the first reactive steps in the combustion oxidation

of paraffin hydrocarbons. In order to avoid ambiguity we are trying to carry out molecular-beam-like experiments so that we can be sure that any product we see is the result of a single collision. Our approach is to employ uncollimated opposing beams of oxygen and hydrocarbon molecules comprising free jets from small sonic nozzles exhausting into an evacuated region. After a collision both reactant and product molecules are collected on a cryogenic trap. Collection can continue for suitably long periods of time so that detectable amounts of product will be obtained even if the reaction cross section is very small. The reaction chamber is then isolated and heated so that the trapped species return to the gas phase and can be swept out by a stream of helium for analysis by gas chromatography.

We have built the reaction system and have tried a number of runs without yet obtaining evidence of reaction. The absence of product may mean that the cross section is too small for us to detect. We think that the likely product may be the olefin corresponding to the paraffin feed, i.e., butene from butane. Because the separation of these two peaks is not all that great, the apparent absence of any product may be due to the "loss" of a small product butene peak in the large reactant butane peak. Consequently we have been trying to carry out partial fractionation of the reactant-product mixture before analysis. So far we have been unsuccessful. Therefore, we are now preparing to run a reaction which should have a larger cross section and whose products should be more easily resolved on the chromatograph. Our candidate is the "oxidation" of hydrocarbon by chlorine to form HCl and an alkyl chloride.

B. Evaporation and Combustion of Droplet Arrays. In previous work we have used the method-of-images to solve Laplace's equation for the combustion of arrays of interacting but slowly evaporating fuel particles. The results

indicated that under typical conditions for spray combustion the droplets burn in a group mode with a common flame rather than as aggregations of single particles each with its own flamelet.[1] It became of interest, therefore, to extend the method to the case of rapidly evaporating droplets. In this case, the convective terms associated with vapor transfer (Stefan flow) cannot be neglected. The presence of these terms makes the rapid evaporation transport equations non-linear. Hence, they cannot be solved directly by superposition.

By means of suitable transformations we have reduced the equations to a form which can be solved by the images method as previously described. It turns out that the particle-particle interactions can substantially reduce the burning rates of fuel droplets even for fairly large particle spacings, i.e., of the order of 30 particle radii. Moreover, the so-called "D^2-Law", which asserts that the surface area of an isolated burning droplet decreases linearly with time, does not hold in the case of interacting droplets.

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HIGH-TEMPERATURE FAST-FLOW REACTOR
CHEMICAL KINETICS STUDIES

AeroChem Research Laboratories, Inc., Princeton, NJ 08540

Arthur Fontijn, Principal Investigator

No work has been undertaken in this project since October 1977 in view of funds for extension of contract not being in hand.

EXPERIMENTAL AND THEORETICAL STUDIES OF MOLECULAR COLLISIONS AND CHEMICAL INSTABILITIES

Massachusetts Institute of Technology, Cambridge, Massachusetts
Subcontract No. 8960-3

Professor John Ross, Chief Investigator

The Final Report on this subcontract is under preparation.

III. MEASUREMENTS

TURBULENT STRUCTURE DETERMINATION BY RAMANOGRAPHY

Yale University, New Haven, Connecticut
Subcontract No. 8960-29

Professor R. K. Chang, Principal Investigator
Mr. M. Long, Assistant in Research
Mr. B. Webber, Assistant in Research

Introduction

The purpose of our research is to develop new spectroscopic techniques that are capable of providing fundamental information in the areas of turbulence and combustion. Presently, we are investigating approaches to measure the instantaneous concentration profile of specific gases in a jet, the instantaneous temperature within a flame, and the velocity flow field in a jet. All three of these optical techniques are being pursued on a well calibrated nozzle and a steady non-luminous flame.

Discussion

Concentration Profile. The concentration profile of a specific gas is determined by measuring the Raman scattering intensity of that gas within a one-dimensional track defined by the laser radiation. Instantaneous mapping of the Raman intensity along this track is accomplished by using a pulsed laser to provide the high energy incident radiation and a low-light level TV camera to detect the weak Raman scattered radiation which has been isolated from the elastically scattered radiation by a double monochromator or an interference filter centered at the Raman wavelength. In order to freeze any small scale turbulent structure (10^{-2} cm) with a flow field (velocity between 10^2 - 10^4 cm/sec), the laser pulse duration needs

to be as short as 10^{-6} sec. However, the requirement for the minimum number of Raman photons for a reasonable signal-to-noise ratio demands that the ruby laser has about 10 Joules per pulse. We are developing a nonlinear-optical method to stretch a conventional Q-switched ruby pulse from 50×19^{-9} sec to 10^{-6} sec. Once the Raman intensity profile is in the computer, we can calculate its autocorrelation, which should be identical to the density autocorrelation function within a time interval defined by the pulsed laser duration.

Temperature Measurement. The temperature averaged along a laser track passing through a flame is determined by detecting the spectral lineshape of the Stokes Raman or anti-Stokes Raman radiation emanating along this track. The Stokes Raman lineshapes consist of a series of peaks arising from vibration transitions $V=0\rightarrow1$, $V=1\rightarrow2$, and $V=2\rightarrow3$, while the anti-Stokes Raman lineshapes correspondingly consist of $V=1\rightarrow0$, $V=2\rightarrow1$, and $V=3\rightarrow2$ peaks. Furthermore, the asymmetrical lineshape of each peak contains information on the rotational temperature. Instantaneous determination of the temperature within an H_2-air porous plug burner is achieved by using a pulsed laser as the incident radiation source, the spectrograph to disperse the spectral content of the Raman radiation (Stokes or anti-Stokes), and a low-light level TV camera to record the entire Raman spectral lineshape from the laser track which passes through the flame. The vibrational and rotational temperature profiles along this track can be deduced by curve fitting the observed lineshapes with the aid of the computer.

Velocity Flow Field. The velocity flow field within a jet is accomplished by seeding the jet with 0.3μ particles and observing their bright trajectories upon illumination of a properly shaped light pulse or a series of short light pulses. This technique is a Lagrangian approach since information is obtained by following the trajectory of a particle. The hot-wire anemometer or the LDV is a Eulerian approach where the particle enters a volume element fixed in the laboratory frame.

Immediate Plans. The one-dimensional concentration profile measurements have been initiated using a cw argon laser and a round nozzle emitting Freon-12 gas in air. Velocity flow field measurements using the two-dimensional capability of our TV camera have also been started. We shall continue the concentration and velocity flow field measurements and then combine this information with the time-resolved velocity data deduced from a hot-wire anemometer in order to fully characterize the nozzle under various initial conditions.

Electronic conversion of our detection system to record two-dimensional information has been completed. This will enable us to map out the two-dimensional concentration profile within a plane defined by the laser beam, as well as the one-dimensional temperature profile along a laser track. Computer software needs to be developed before we can test the sensitivity of our low-light level TV camera system, as we know that the Raman signal will be reduced by the number of resolvable elements in the second dimension.

Semi-Annual Progress Report

CARS INVESTIGATIONS IN SOOTING FLAMES

United Technologies Research Center
East Hartford, Connecticut 06108
Subcontract 8960-28

Alan C. Eckbreth, Principal Investigator

Introduction

Laser Raman spectroscopic techniques for combustion diagnostics have undergone considerable development in the past several years and are now being employed in a variety of fundamental flame investigations. Instrumentally however, practical combustion devices possess flame environments which differ markedly from those typically (laminar premixed, hydrogen diffusion) employed in fundamental studies. Practical devices contain flames which can be highly particulate laden and hence, luminous, if hot, and turbulent. These conditions lead to a variety of severe, naturally occurring or laser induced interferences which must be overcome. Of these, laser modulated particulate incandescence appears to be the most severe. When the soot particulate loadings become moderate, on the order of 10^{-8} gm/cm^3 or larger, the spontaneous Raman signal to laser modulated soot incandescence interference ratio can become unacceptably low for measurement purposes.

Coherent anti-Stokes Raman spectroscopy (CARS) appears as an attractive alternative to spontaneous Raman scattering for practical combustor diagnosis. First, the CARS process generates signals generally several orders of magnitude greater than those possible with spontaneous Raman scattering. Second, the CARS radiation emerges as a coherent beam which can be completely collected using high f number collecting optics and spatial filtering. This not only leads to high signal collection efficiency, but low interference collection as well due to the greatly reduced solid angles employed. CARS signal strengths appear adequately large to overcome interferences from both natural background luminosity and laser modulated particulate incandescence. However, CARS generation in sooting flames had not been demonstrated. In sooting flames, there is the potential for the

generation of nonlinear interferences from soot particulates and soot vaporization products. The objective of the present research is to address CARS generation in sooting flames, to examine and develop techniques to suppress nonlinear interferences, and to perform CARS temperature measurements in such flames. Such a program logically precedes measurement attempts in actual research scale combustors.

Discussion

CARS generation has been studied in a laminar, sooting, propane diffusion flame. Such a flame was studied extensively earlier in conjunction with the investigations of laser modulated soot incandescence interferences in spontaneous Raman diagnostics (Refs. 1, 2). The flame is sustained on a 0.6 cm i.d. stainless steel tube. The flame in appearance resembles that of a candle and is highly sooting. Previous Mie measurements (Ref. 1) indicated a soot number density on the order of 10^{10} cm^{-3} with an average particle diameter of 400Å. This is a very high soot level producing an attenuation in transmitted light of a few tenths of a percent per mm pathlength, thus serving as a rigorous test of the capabilities of CARS. To obtain the requisite spatial resolution, a crossed-beam phase-matching approach (Ref. 3) developed at UTRC is employed. The technique is termed BOXCARS based upon the shape of the phase-matching diagram, and crosses three beams, two "pump," one "Stokes" at appropriate angles to generate phase-matched CARS. The technique circumvents the poor and often ambiguous axial spatial resolution encountered with conventional, collinear phase-matching. In the initial experiments, the CARS was generated in a sample volume approximately 0.4 mm in dia by 1 mm long. The UTRC CARS apparatus employs a frequency-doubled neodymium laser to provide a pump component at 5320Å, part of which is split off to generate a tunable broadband "Stokes" component from a laser pumped dye oscillator/amplifier combination.

In the first experiments performed, strong incoherent and coherent interferences, roughly comparable to the signal from the ground vibrational state of N_2 were encountered. Incoherent features are generally suppressible in coherent spectroscopy. Coherent features are obviously more problematical. In this instance, the coherent feature arose from three wave mixing in laser produced C_2. At the high laser intensities used to produce CARS, significant soot vaporization will occur. This occurs on even a nanosecond time scale as a study of the incoherent emissions here demonstrated. This is due to an absence of adequate heat transfer processes leading to a flashed vaporization of the soot surface. A major product of soot vaporization is C_2. CARS can be electronically resonantly enhanced when either the CARS radiation itself or the pump component resides near an electronic transition. The CARS generation in the laser produced C_2 vapor is resonantly enhanced because

of the coincidence of the N_2 CARS and C_2 electronic transition frequencies. C_2 has a major Swan band transition, $A^3\Pi_g$ (v=0) → $X'^3\Pi_u$ (v=1), at 4737.1Å midway between the N_2 anti-Stokes bands at 4733Å (v=0) and 4740Å (v=1).

An optical collection system was set up at right angles to the central axis and the laser induced emissions examined through blocking and narrowband interference filters. Both laser modulated incandescences and laser induced Swan emissions were examined. The Swan emissions were about an order of magnitude more intense than the incandescences and found to be more pronounced with the broadband emission centered at 6073Å than with 5320Å excitation, probably due to the presence of three Swan absorptions within the broadband (270 cm^{-1} FWHH) 6073Å Stokes laser band. This result suggested decreasing the dye laser spectral bandwidth to decrease the C_2 Swan absorptions and to increase the CARS signal strength. Also insertion of a polarization filter in the polarized CARS beam reduces any remaining incoherent contributions in half. In so doing, fairly clean N_2 spectra were obtained which exhibited minimal C_2 interferences and which permitted a temperature measurement in the flame of approximately 2300°K. The adiabatic flame temperature for propane/air is 2250°K. The foregoing result is very encouraging since the soot densities in the propane flame are quite high and is a favorable indication of the practical viability of CARS diagnostics.

Experiments are continuing in this vein to optimize the Stokes laser bandwidth and to map out the temperature field in a highly sooting flame. The CARS temperature measurements will most likely be compared with those determined by sodium line or soot reversal techniques.

Notes and References

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LASER RAMAN PROBE FOR COMBUSTION DIAGNOSTICS

General Electric Company, Corporate Research and Development
Schenectady, New York
Subcontract No. 8960-17

Marshall Lapp, Principal Investigator
C. M. Penney, Physicist
S. Warshaw, Physicist

Introduction

Fluctuation values of temperature have been obtained from vibrational Raman scattering (RS) data for a hydrogen-air turbulent diffusion flame produced in a coaxial jet combustor. These data, in the form of histograms as well as average values, give radial profiles of temperature at distances downstream of the fuel pipe tip corresponding to 1 to 100 tip diameters. Additional information on instantaneous values of flame stoichiometry has also been found. Experimentation is in progress on coupling the RS apparatus to laser velocimetry (LV) equipment, in order to produce essentially simultaneous temperature and velocity flowfield information.

Discussion

During the past reporting period, we have focused upon preparations for interfacing the RS apparatus with LV instrumentation for obtaining

turbulent velocity data in the same small spatial volume and over the same short time duration as for the RS data. We have performed some prototype experiments to investigate key elements of this work. We have also obtained substantially more fluctuation temperature values from RS Stokes/anti-Stokes data for our turbulent jet diffusion flame combustor, and are continuing adjunct calibration and other ancillary experiments to make the data interpretation more meaningful.

The fluctuation temperatures have been determined for the co-flowing combustor described in previous reports, consisting of a movable 3 mm diameter fuel tube surrounded by a 100 mm diameter air pipe. Turbulent diffusion flames are produced with a hydrogen fuel flow of about 585 cm^3/s and an air flow of about 0.1 m^3/s, and the flame observed in a short open-throat section. The RS data have been taken utilizing a modified Phase-R dye laser source, which results in an experimental time resolution of about 1/2 μs. The spatial resolution, determined by the collection optics and the laser beam focusing properties, is roughly 1/2 mm^3, with no characteristic dimension greater than about 0.8 mm.

The temperature is determined from the ratio R of integrated Stokes vibrational scattering intensity to the integrated anti-Stokes vibrational scattering intensity, viz.,

$$\begin{aligned} R &= \text{const.} \times \exp\,(hc\omega_0/kT) \qquad (1) \\ &= \text{const.} \times \exp\,(3374/T) \text{ for nitrogen,} \end{aligned}$$

where h is Planck's constant, c is the speed of light, ω_0 is a vibrational term value constant for the gas under consideration, k is Boltzmann's constant, and T is the temperature in °K. The constant of proportionality in Equation (1) is best determined by empirical calibration of the light-scattering optical detection system through use of a test medium of known

temperature, and has been done here through use of premixed hydrogen-air flames burned on a porous plug burner for which temperatures were accurately determined in previous experiments (many of which were carried out under Project SQUID sponsorship).

The calibration experiments showed excellent agreement among the average temperatures of three different flames (viz., from stoichiometric to lean premixed laminar H_2-air flames), using only one of these flames to determine the empirical constant in Equation (1). (This constant, which is completely determined by the optical and signal processing characteristics of our measurement system and is thus not "adjustable" in any sense, can also be found through use of purely optical and electronic calibration experiments for the spectroscopic and electronic detection apparatus. Such measurements are now in progress.)

The relatively small statistical variation of these temperature data was found to be reasonable from the point of view of our experimental parameters. (For example, one run of 50 shots for which the average value was 1807°K produced probable error bounds of ±79°, corresponding to measurement bounds within which any particular temperature could fall with 50% probability.) Since the instantaneous values of temperatures observed for the turbulent coaxial combustor were found to have fluctuations far in excess of the error bounds in the laminar flame calibration experiments, they are convincingly ascribed to the thermal fluctuations of the diffusion flame. The temperature histograms (or probability distribution functions) are broader and show more structure than was expected, but the causes of these phenomena are still speculative. The effect of intermittancy at the flame boundaries (i.e., in zones of strong ambient air mixing) is quite clear, but additional histogram-broadening effects due to flame oscillations may

exist. Further work in defining the problems involved in the interpretation of the histograms is in progress; one likely result will be the redesign of our combustion facility to incorporate a closed throat square test section and a suction pump at the exhaust rather than a fan blower.

Additional data of use in interpreting the temperature histograms are given by associated N_2 density histograms, which can be related to estimates of local flame stoichiometry. Current work involves interpretation of these density histograms for their utility in providing additional insight concerning the true temperature flowfield.

The histograms obtained for our system show strikingly the usefulness of instantaneous data acquisition for temperature. Progressing to closely-simultaneous temperature and velocity data acquisition should result in an even clearer demonstration of the value of optical light-scattering diagnostics. Toward this end, we are presently making operational new LV instrumentation and are completing interface equipment for coupling the RS and LV portions of the experiment. We are also moving from manual RS data acquisition (i.e., photographic records of oscilloscope traces for individually-initiated experimental shots) to microcomputer-controlled digital data acquisition using a Nicolet Explorer III dual digital oscilloscope, which will permit us to effectively couple with the new LV processor. The computer initially will use an extended version of the BASIC programming language to compute and store temperature values as well as the velocity data from the LV processor. This microcomputer will also be connected directly to the GE CRD mainframe computer in order to use effectively previously-developed data reduction and computing routines.

Notes and References

Recent publications and manuscripts related to this research effort supported by Project SQUID and by other parallel General Electric and government efforts are listed below:

1. M. Lapp, "Raman Scattering from Water Vapor in Flames," AIAA J. 15, 1665 (1977).

2. M. Lapp, "Probing Flames with Lasers," General Electric R&D Review, 1977; translated into French as "Le laser explore les flammes," in La Revue Polytechnique No. 1364, 8/77; translated into German as "Flammenuntersuchungen mit dem Laser," in Chimia 31, No. 10, Oct. 77.

TURBULENCE MEASUREMENTS

IN JETS FLAMES AND COMBUSTORS

Polytechnic Institute of New York
Aerodynamics Laboratories

Subcontract No. 8960-5

S. Lederman - Principal Investigator

Introduction

In the last semiannual report of September 12, 1977, data concerning concentration temperature, velocity, turbulence intensity and the mixedness parameter in a methane air CO_2 flame were obtained. In this reporting period, a particular set of experiments concerned with the applicability of the spontaneous Raman diagnostic method to systems containing carbon molecules were conducted. In addition some experimental results on a sooty flame utilizing CARS were obtained.

Discussion

The applicability of the spontaneous Raman effect to the diagnostics of flow fields encountered in propulsion and combustion has been a major part in the development of nonintrusive techniques. As it is well known, this technique is applicable not only to the measurements of concentration and temperature[1-3], but also to the measurement of fluctuation intensity of the concentration and temperature[4-8] and therefore to the fluctuation intensity of the density in a flow field. It has also been shown[9], that the correlation of the second and higher orders can also be

measured using the spontaneous Raman effect.

It is therefore important to determine if the presence of soot in the flow field renders the Raman diagnostic technique useless. A preliminary series of tests on a pure methane air flame, and a methane air flame with the addition of carbon particles were performed. Some results are shown in Fig. 1 and 2.

Using the Coherent Antistokes Raman Scattering system, some measurements were made on a methane flame with varying quantities of soot. The measured specie was the unburned methane in the flame as a function of X/D. Some results are shown in Fig. 3 and 4.

It should be noted that an attempt was made using the Spontaneous Raman effect to determine the unburned methane in this flame using the same Q-switched Ruby laser at a power level of over 100 megawatt peak power. No signal could be detected due to the very low concentration of the remanent methane.

References

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3. Lederman, S. and Bornstein, J.: "Temperature and Concentration Measurements on an Axisymmetric Jet and Flame". Technical Report No. PIB-32-PU, December 1973.

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7. Lederman, S.: "Temperature, Concentration Velocity and Turbulence Measurement in Jets and Flames". Technical Report No. PINY-76-10 December 1976, Project SQUID, Purdue University.

8. Lederman, S.: "The Use of Laser Raman Diagnostics in Flow Fields and Combustion". Progress in Energy Comb. Sci., 3, pp. 1-34, 1977, Pergamon Press.

9. Lederman, S. and Celentano, A.: "Application of the Integrated Raman and LDV System". Polytechnic Institute of New York, M/AE Report No. 78-5. Project SQUID Report PIB-35-PU.

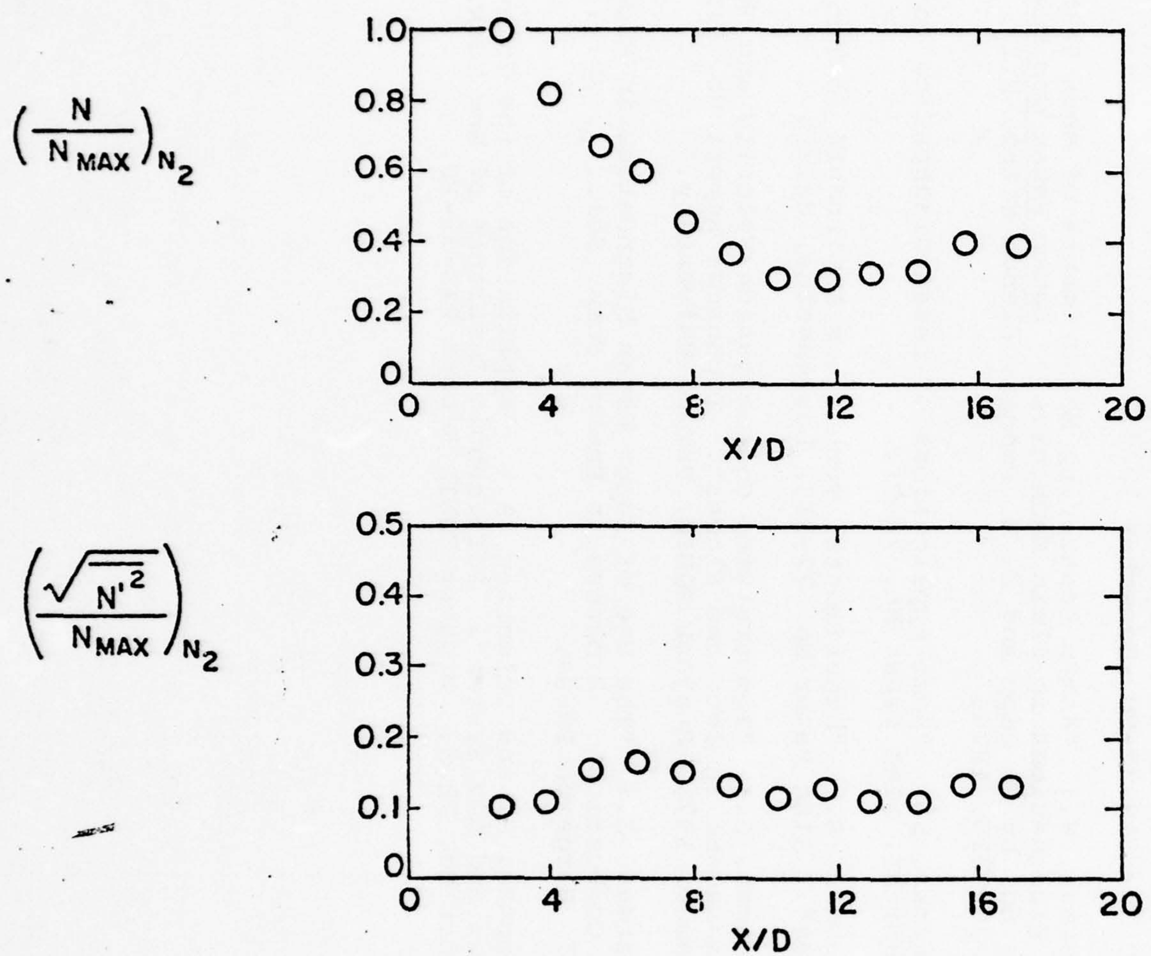


FIG 1 CENTERLINE CONCENTRATION AND TURBULENT INTENSITY OF N_2

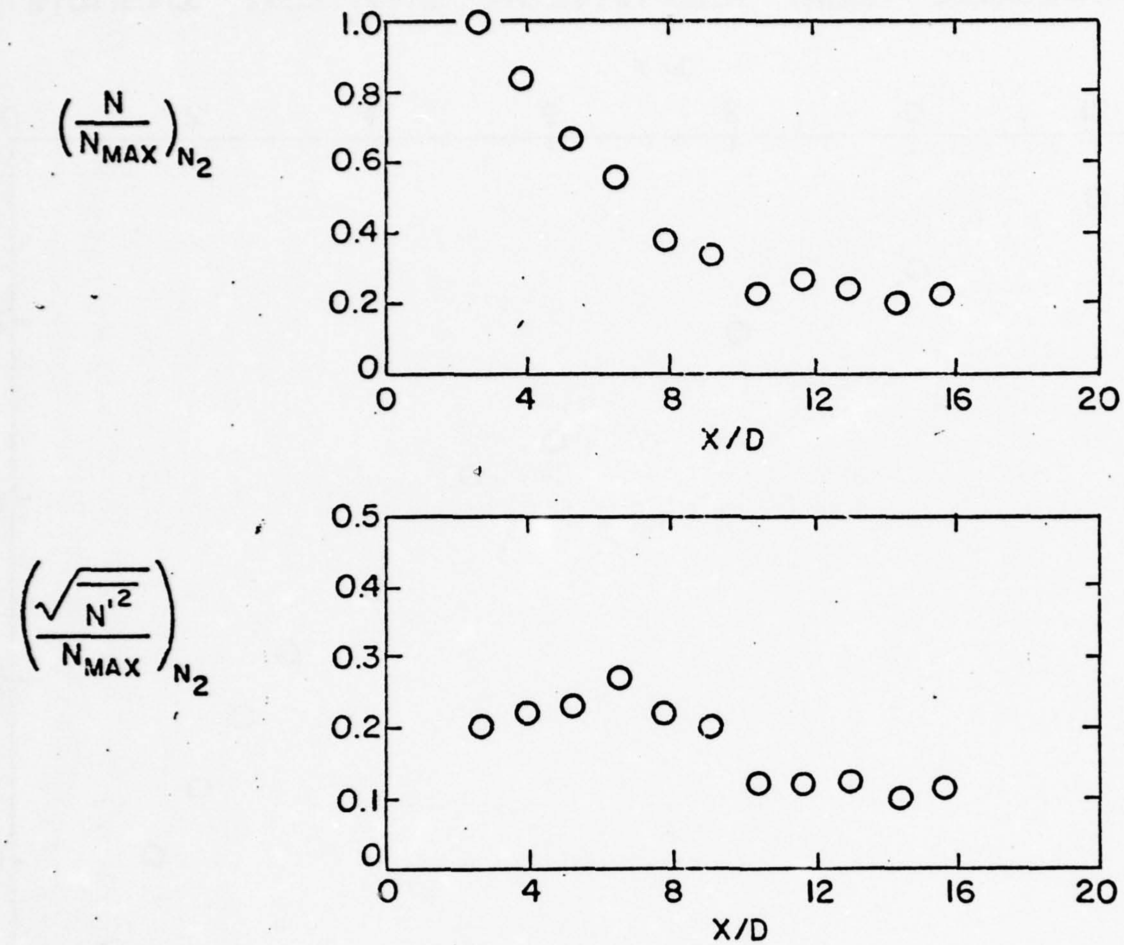


FIG 2 CENTERLINE CONCENTRATION AND TURBULENT INTENSITY OF N_2 IN THE PRESENCE OF CARBON PARTICLES

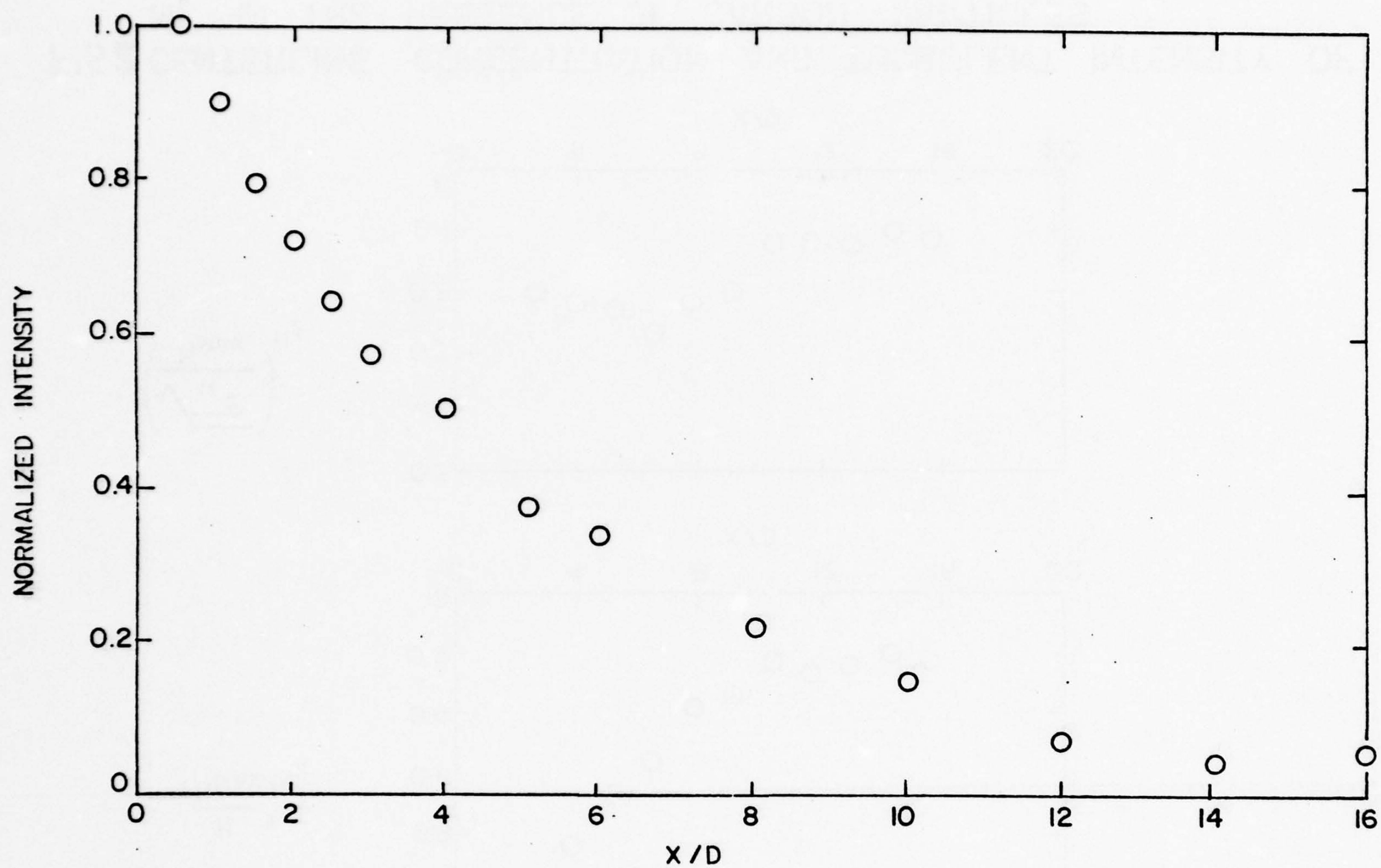


FIG3 UNBURNT METHANE NORMALIZED WITH RESPECT TO MAXIMUM

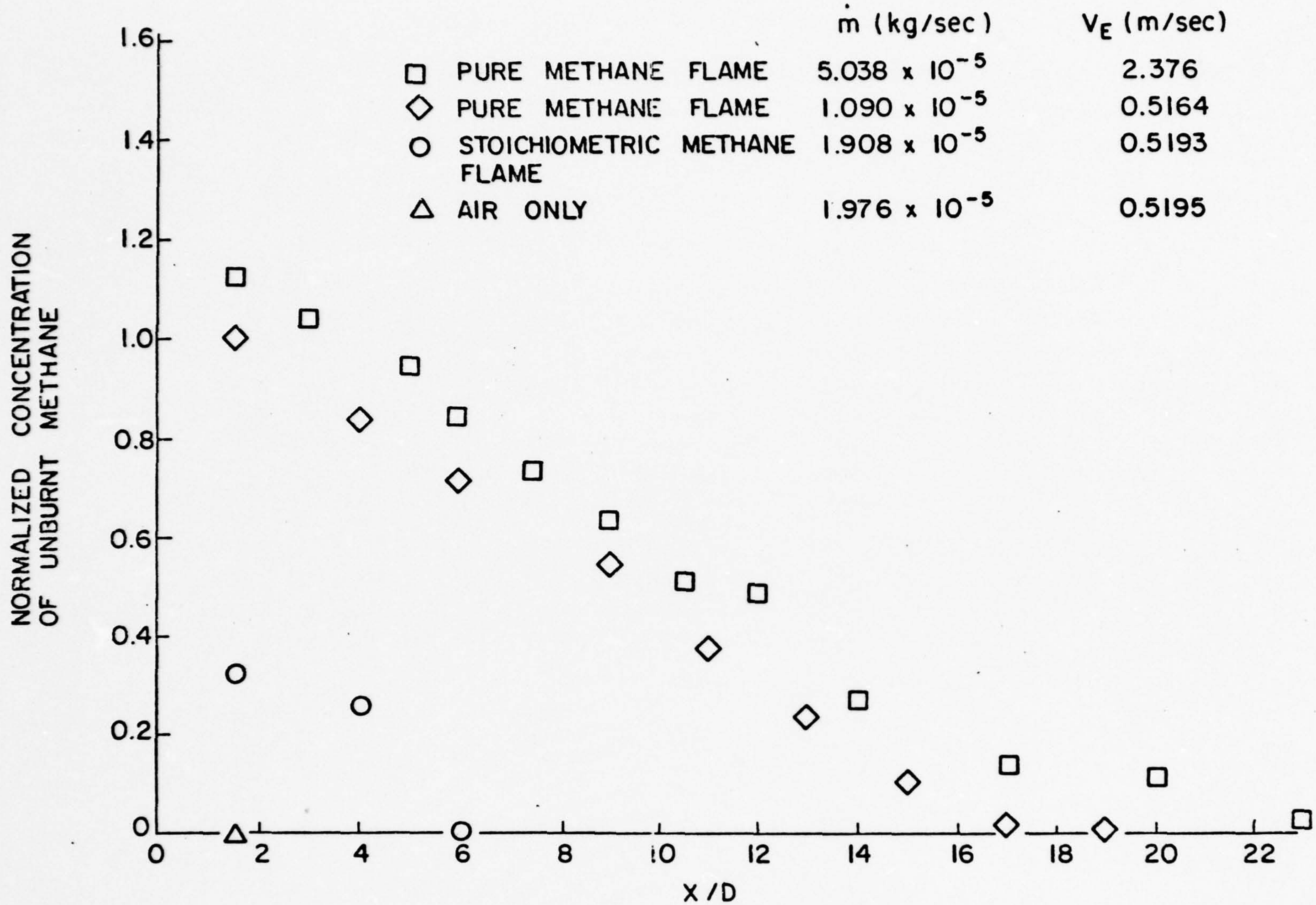


FIG 4 CONCENTRATION OF UNBURNT METHANE

IV. TURBULENCE

Semi-Annual Progress Report

LARGE SCALE STRUCTURE AND ENTRAINMENT IN THE TURBULENT MIXING LAYER

University of Southern California, Los Angeles, California
Subcontract No. 8960-12

Professor F. K. Browand, Principal Investigator
Mr. B. O. Latigo, Research Assistant

Introduction

Previous visual observations indicate the presence of large scale, quasi-organized, vortical lumps aligned across the flow (LSS) in the two dimensional mixing layer. The existence of these structures--documented visually over a range of Reynolds numbers extending from 10^3 to 10^7 -- is suggestive of their importance as a characteristic feature of the turbulent flow. As the mixing layer grows downstream, the vortices must necessarily interact to form larger vortices. The interactions-- to a certain degree--are distinct and repeatable, and it is precisely these interactions which are responsible for the growth of the mixing layer. The present experimental study, carried out in a wind tunnel at Reynolds numbers 10^6, is intended to provide more information about this large scale structure.

Discussion

The procedure for studying large scale structure has been to form an ensemble average of individual interactions to produce a composite interaction. The usefulness of this approach depends critically upon the ability to detect or sample repeatably, similar interactions. We have recently improved our sampling technique by introducing a small acoustical disturbance at the splitter plate trailing edge, using a linear array of

speakers mounted in the tunnel roof. We wish to introduce a disturbance which will augment the naturally occurring interactions without altering their fundamental character.

The acoustical augmentation produces several readily observable effects. First, the large vortical structures, which grow downstream by coalescence, are phase locked with the forcing signal. The interactions between these structures occur at fixed spatial locations. Second, the large vortical structures are more organized and repeatable than without forcing. An indication of this increased organization is illustrated in figure 1, where cross correlations between pairs of hot wires at various spanwise separations are shown. The correlations on the left result when no forcing is applied. Now intermittant forcing is applied and ensembles of velocity fluctuation at different spanwise stations are formed using the forcing to establish an origin in time. Cross correlations of the ensemble averages are shown on the right of figure 1. There is practically no loss of correlation across the span of the wind tunnel, indicating that slight forcing is sufficient to produce structures which are remarkably two-dimensional.

There is much work to be done in understanding the interactions of these large scale structures, but preliminary results suggest the following conclusions:

i) Pairing interactions do occur at these large Reynolds numbers, and are qualitatively similar to the interactions at much lower Reynolds numbers.

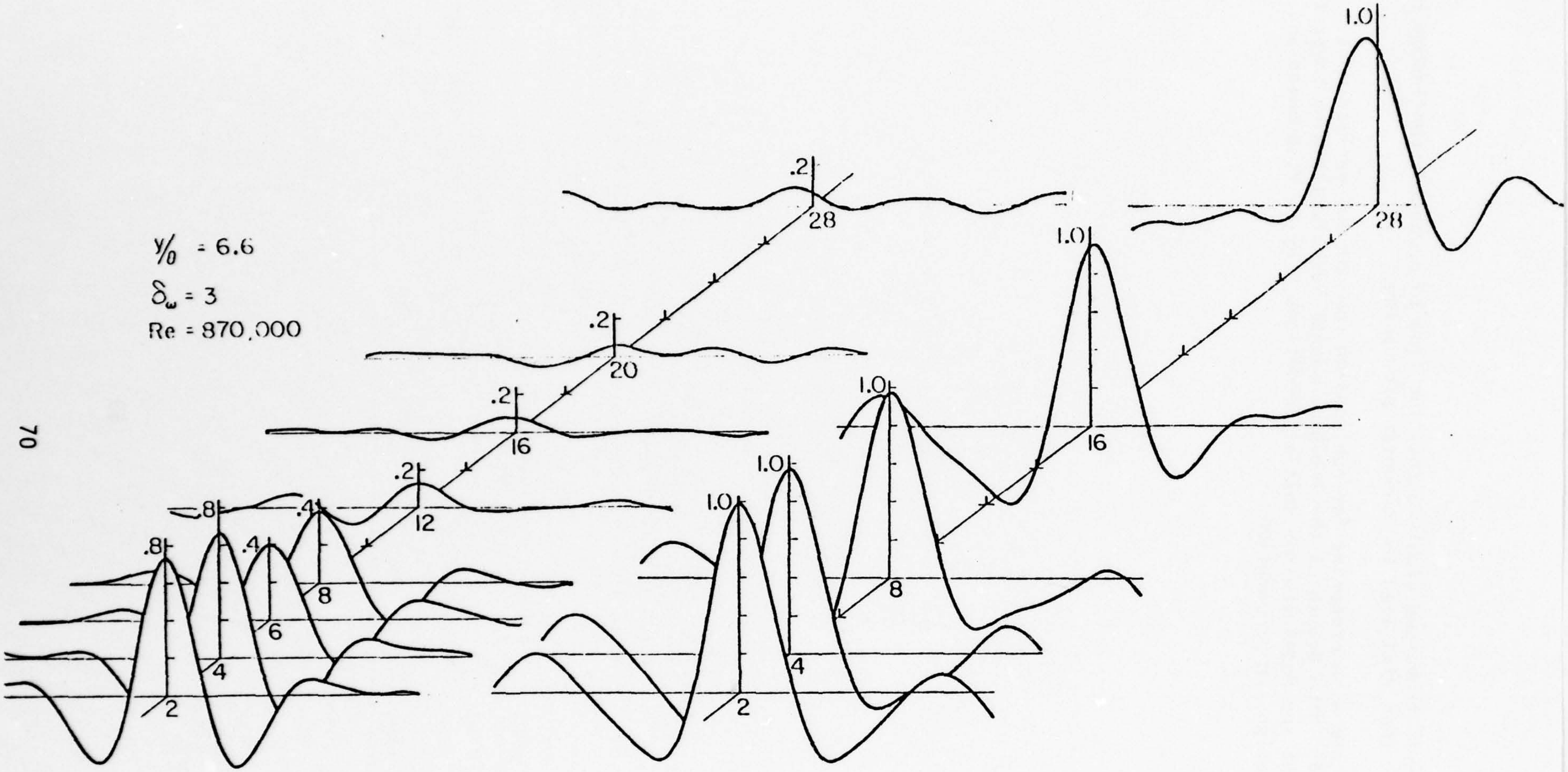
ii) The presence or absence of the forcing does not alter the major features of the interactions.

iii) The interactions between the large scale vortices are responsible for the bulk of the observed Reynolds stress. This result can be seen in two ways. First by filtering the signals, the contribution to $\overline{u'v'}$ from different frequency bands can be assessed. Figure 2 shows the long-time averaged product $\overline{u'v'}$ for the bandwidth DC to 2.5 KHz, compared to the contribution from frequencies above 280 Hz. The passage frequency at this downstream location is 70 Hz. It can be concluded that the bulk of the Reynolds stress arises from low frequency components comparable to the passage frequency. This conclusion is independent of any assumption about the existence of particular large scale structure. Some idea of the importance of the interaction of the vortical features can be obtained by calculating the contribution (to the long time average $\overline{u'v'}$) of the ensemble averaged field, $u_E v_E$, during the passage of the interaction. Figure 2 shows this contribution when the interactions are assumed to occur at the passage frequency. It is seen that such interactions could account for the major portion of the (long time averaged) Reynolds stress, although the lower values in the center of the mixing layer may mean we are not centered correctly in the interaction.

At present, two components of velocity are being measured (with hot-wires) at a number closely spaced downstream stations. At each station

the wire is traversed slowly across the flow to produce a continuous record which is then digitized for computer processing.

We are also preparing for publication some of our earlier work entitled: "The Growth of the Two-Dimensional Turbulent Mixing Layer from Turbulent and Non-Turbulent Initial Conditions," by F. K. Browand and B. O. Latigo, in preparation.


y/δ = 6.6
δ_ω = 3
Re = 870,000
.8
.8
.4
.4
.2
.2
.2
.2
1.0
1.0
1.0
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2
4
6
8
12
16
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28
2
4
8
16
28

FIGURE 1

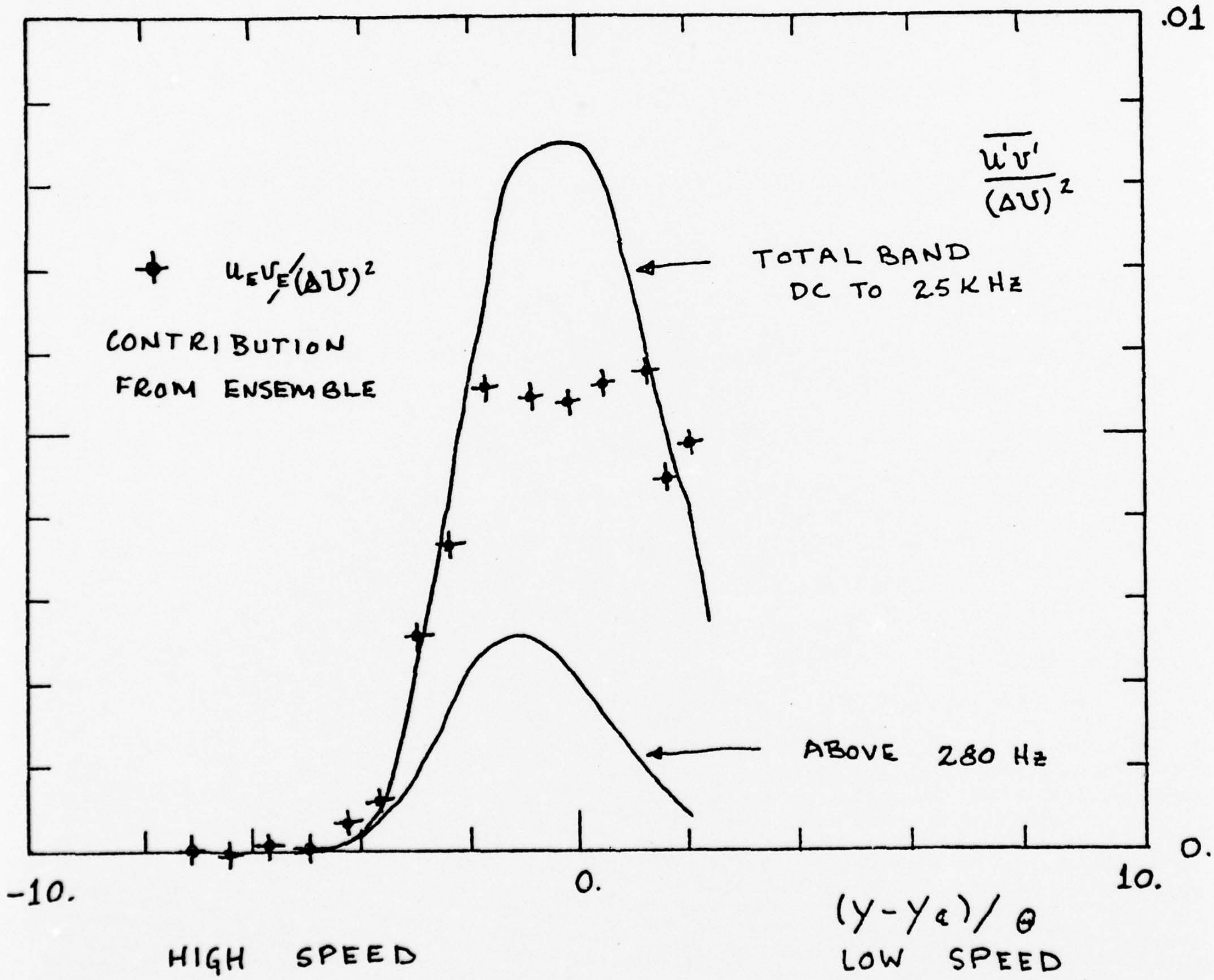
.01
$\overline{u'v'}/(\Delta U)^2$
$u_E v_E/(\Delta U)^2$
CONTRIBUTION FROM ENSEMBLE
TOTAL BAND DC TO 25 KHz
ABOVE 280 Hz
0.
-10.
0.
10.
$(y-y_c)/\theta$
HIGH SPEED
LOW SPEED

FIGURE 2

Semi-Annual Progress Report

THE STRUCTURE OF EDDIES IN TURBULENT FLAMES

University of Sheffield, England
Subcontract No. 8960-30

Dr. N. A. Chigier, Principal Investigator
Dr. A. J. Yule, Research Fellow

Introduction

An experimental study is being carried out on the structure of turbulent propane/air diffusion flames. Within the mixing regions of round turbulent jets, ring vortices can be detected and followed as they break down into individual eddies. The flame characteristics are dependent upon mixing of fuel and air and presence of coherent eddies can result in unmixedness. The main aim of this study is to relate high-speed photographic evidence of formation and movement of eddies and flamelets with time-resolved measurements of velocity and temperature. Variation of velocity with time is measured using a single particle counting forwardscatter laser anemometer, specially developed for conditional sampling of velocity in turbulent flames. Temperature variation with time is measured with fine wire thermocouples with direct compensation by interfacing with a computer.

Discussion

The apparatus, consisting of a central burner installed in a settling chamber, has been constructed to provide uniform constant velocity with varying turbulence levels in the central jet and in the surrounding secondary flow. Propane is partially premixed with air containing SiO_2 seeding particles for supply to the central burner. A cyclone-seeding apparatus has been constructed for the central flow seeding and the secondary flow is seeded separately by a high throughput fluidized bed seeder. In order to minimize biasing errors in velocity measurements in the flame,

seeding levels in the inner and outer flows require to be equal and maintained at a constant level throughout the experiment. Problems have been encountered with seeding particles settling on screens introduced for smoothing the flow. The laser anemometer has been used to measure exit velocity profiles and achieve optimum design of the screens in order to produce low turbulence profiles at the exit of both the inner burner flow and the outer air flow.

Photographic studies have been made of partially premixed propane/air diffusion flames. These studies have been used to locate the flame region and select flow parameters for detailed measurement studies. As in the case of cold vortex studies previously made by Yule at Southampton, ring vortices can be clearly identified in the flames for a wide range of Reynolds number up to 10^4. It was found that the existence of a vortex ring region depended critically on the initial turbulence level at the exit from the burner. When this turbulence intensity increased above 6%, the vortex rings were observed to lose their symmetry very rapidly.

During experimental runs, it was found that the high seeding densities necessary for high frequency response velocity measurements resulted in rapid clogging of fine gauzes installed for flow smoothing. In order that the initial conditions could remain constant, with low turbulence levels, it was necessary to frequently dismantle and clean the burner assembly. It appears that there is an incompatibility in achieving low turbulence levels using fine wire gauzes and the use of particles for seeding. A redesigned burner is now under construction, which is intended to overcome this difficulty.

During the next six months, vortex ring flames will be studied by simultaneous measurement of velocity using the laser anemometer, and temperature using the fine wire thermocouples. The initial series of measurements will be made in the flame to obtain mean, rms, probability density function and cross-correlations with time delay for velocity and temperature. Visual examination of time histories and photographic studies - with temperature simultaneously recorded on the film - will be used as a basis for designing a conditional sampling technique, which will then be used to study the structure of individual vortex rings.

BINARY GAS MIXING WITH LARGE DENSITY DIFFERENCE IN HOMOGENEOUS TURBULENCE

Studies of the Basic Phenomena Associated with Molecular Diffusivity Effects in Turbulent Mixing

Michigan State University, East Lansing, Michigan
Subcontract No. 4964-49

Professor J. F. Foss, Principal Investigator
Mr. K. C. Cornelius, Graduate Research Assistant

INTRODUCTION

It is the purpose of our research to illuminate, and to provide quantitative measures of the fundamental phenomena which are responsible for the strongly enhanced molecular diffusivity effects in a turbulent mixing field. The presence of these effects is of obvious importance in the combustion process; their full exploitation requires an understanding of their dependence upon the character of the turbulence field. One approach toward this understanding is to examine the results of controlled variations in the governing parameters of experiments which are (1) sufficiently simple that the cause/effect relationships are least ambiguous and (2) sufficiently similar to the technological problem that the phenomena of interest are preserved. Our experiments examine the mixing of two distinct rectangular volumes by light scattering measurements from the central region of a closed mixing chamber. The nature of the experimental facility allows the initial turbulence structure in the two volumes to be individually controlled and stable, unstable or neutral density mixing may be investigated.

The first set of experiments using this unique facility has been completed. The lower volume was contaminated with submicron particles, which allowed the non-diffusive mixing of the upper and lower volumes to be observed by noting the presence or absence of the marking contaminant in small sample volumes. The volumes are defined by a 0.25 mm (focused) laser beam and the 0.35 mm height was defined by a helical slit in a rotating disc located at the plane of the recreated laser beam. Each scan (by a slit) sampled 205 locations along a 74 mm line parallel to the concentration gradient; the scan was executed in 3.11 msec (= 0.768 M/U_o) and the concentration $\Gamma(Z,t)$ was denoted as 1 or 0 depending upon the presence or absence of the

contaminant. A data base of 69 experiments with air/air and 100 experiments with Freon 12/Freon 12 was acquired. These experiments were to establish the experimental technique for the simplest case of neutral density mixing and they were to establish the influence of the kinematic viscosity on the mixing field ($\nu_{air} = 5.8\ \nu_{Freon\ 12}$). These objectives have been met. The experiments and the associated analyses form the basis of the Ph.D. thesis for Mr. K. C. Cornelius. The thesis was defended in February and is in the stage of final revisions and typing. The SQUID report to be written from it will be forthcoming.

DISCUSSION

The objective reporting of the experiments, which was noted as being essentially complete in the previous semi-annual progress report, has been considerably extended by the development of additional theoretical analyses. Width and displacement measures have been obtained for the ensemble average of the instantaneous scans once these are shifted into alignment with respect to their instantaneous centers. The measures, so defined, reveal that the centerline displacements are insensitive to the six fold change in kinematic viscosity (as would be expected but that the relative width of the instantaneous scan is dependent upon this fluid property. (Note, U_o and M are identical for the air and Freon 12 test gases; $\nu_{air} = 5.8\ \nu_{Freon\ 12}$). It is also shown that the ensemble average mixing field width is closely approximated by the same measure from the instantaneous scans and that the Reynolds number independent gross transport makes only a small contribution to the observed width.

The second theoretical development exploits the observation that -- $\langle\Gamma(Z,t)\rangle$ (the ensemble averaged concentration distribution) can be directly related to the dispersion of a single particle -- in order to infer the Lagrangian microscale and macroscale. The presence of the decaying turbulence field is acknowledged by utilizing the basic proposal of Townsend (1954) and extending the analysis of Shlien and Corrsin (1974). This improved analysis allows the data to be evaluated in terms of the laboratory (normalized) time coordinate instead of in the stretched time coordinate; the Shlien and Corrsin data are reinterpreted with the new formulation. With respect to the present results, the new theory supports the observation that the air dispersion is greater than that for the Freon. The difference exists in the Reynolds number dependence of the Lagrangian micro scale; details are provided in the full report.

The identification of the kinematic viscosity influence on the mixing (dispersion) phenomenon is important for the projected large density difference experiments. It was earlier suspected that the differences in the Freon 12 and air results were a result of sub-scattering volume mixing. The results from the instantaneous scans and the dispersion measurements provide independent confirmation that this potential problem was not the basis for the observed differences. The projected experiments will have to be interpreted with the understanding that the Lagrangian microscale is larger in the more viscous gas.

Semi-Annual Progress Report

HETEROGENEOUS TURBULENT FLOWS RELATED TO PROPULSIVE DEVICES

University of California, San Diego
Subcontract No. 4965-26

Paul A. Libby
Principal Investigator

Introduction

This research addresses problems related to the turbulent heterogeneous flows which arise in a variety of propulsive devices when reactants and products mix and react. The effort is both experimental and theoretical; the experimental program concerns exploitation and extension of the multiple sensor "hot wire" technique of Way and Libby which permits time-resolved and space-resolved measurements of velocity and concentration of one light species, e.g., helium, in a mixture of light and heavy gases under isothermal conditions. The application of this technique in the present research is to a confined internal flow corresponding to an idealized combustor. The related theoretical work supports the experimental effort and attempts to extend the results thereof to flow situations of more practical concern, e.g., to chemically reacting flows.

Discussion

In our previous Semi-Annual Progress Report we described work underway on premixed combustion. We have for several years been collaborating with Professor K. N. C. Bray and Dr. J. B. Moss of the University of Southampton on applications of the Bray-Moss model of premixed combustion to planar turbulent flames, both oblique and normal.

Our most recent effort has been concerned primarily with the influence of large but finite values for the two non-dimensional parameters determining the behavior of such flames, a turbulence Reynolds number and a Damkohler number. The original theory, termed first-order, assumes that these two parameters are infinite and we wished to examine the effect of slight deviations from this limit in order to expand the range of comparison with data. This work has been completed and submitted for possible publication as indicated by reference 1.

In the course of the study leading to reference 1 considerable attention was devoted to comparing the predictions of the first-order calculations to experimental data for normal flames. In previous work we had focused on such comparison for highly oblique flames and had established that a value of the one empirical parameter in the first-order theory, namely Φ, equal to 0.1 was required to obtain agreement. The experimental data for normal flames at the highest turbulence Reynolds numbers involve considerable scatter so that an unequivocal value for Φ is difficult to establish. Nevertheless, a value of 1.4, an order of magnitude greater than that needed to achieve agreement for highly oblique flames, seems indicated. We thus observe another example of the shattered hope for "universality" in the constants appearing in turbulence phenomenology. There are, of course, a variety of possible explanations for the discrepancy; in terms of the theory the use of gradient assumptions under the conditions of high rates of strain such as arise in turbulent flames and the neglect of the effect of weak pressure gradients when large density variations are present are two candidates for shortcomings in the theory. With respect to experiment the wide scatter in available data suggests that the experimentalists cannot agree on a fundamental quantity of concern to the theoretician, the turbulent flame speed. We continue research on this problem.

During the past few months a new avenue of theoretical work related to premixed combustion has been initiated. We have been examining the influence of acceleration as may arise in unsteady turbulent flames which are driven hydrodynamically or in horizontal flames propagating steadily in either the upward or downward direction. There appears to have been no previous examination of this influence. Suggestions are made in the literature of Taylor instability as a cause for the onset of turbulence in accelerated laminar flames but we are concerned with the alteration of turbulent flame behavior as a result of acceleration.

From an examination of the describing equations and from a consideration of the only related literature, that concerned with turbulence involving buoyancy, we have deduced that acceleration can have two effects; the first is the alteration of the turbulent kinetic energy balance by a source term proportional to acceleration and to the extent of heat release. The second effect is a more subtle one, namely the alteration

of the flux of product which in Favre-averaging is $\overline{\rho u'' c''}$. In our previous calculations related to unaccelerated flames this flux is modeled in terms of a gradient approximation. Inclusion of the effect of acceleration on this flux appears to require a new theory which would apply to both steady and accelerated flames. Such a theory for normal flames has been formulated but no results are at present available.

Our first calculations of the effect of acceleration on normal flames were based on alteration of only the turbulent kinetic energy balance and show that acceleration can lead to a significant increase in the turbulent intensity through the flame. This is in contrast to the reduction in that energy due to dilatation when the flame is unaccelerated. There is also an increase in turbulent flame speed. However, in view of the possible importance of acceleration on the flux of product we do not consider these results definitive and await the completion and assessment of the new theory before making a definite conclusion on the behavior of flames undergoing acceleration.

During the period covered by this Report we have completed for a DOE Workshop a critique of problems in the phenomenology of turbulent reacting flows (reference 2) and have submitted it for publication in the proceedings of that Workshop.

Preparations for our next experiment involving helium-air mixing are nearing fruition and tests will be run in the next several weeks. Involved will be two distinct experiments. The first will correspond to the tests reported in reference 3 and will involve helium at ambient temperature discharged into a moving airstream. These tests will complement and supplement the data in reference 3 and will permit that research to be submitted for publication in the open literature. The second experiment will involve heating of the helium in order to provide data on the behavior of two scalars in turbulent shear flows. There are at the present no data of this sort and yet there is considerable fundamental interest since the molecular properties of the two scalars differ significantly.

References

1. Libby, P. A., Bray, K. N. C. and Moss, J. B., "Effects of Finite Reaction Rate and Molecular Transport in Premixed Turbulent Reacting Flows," Combustion and Flame (submitted).

2. Libby, Paul A., "Some Problems in the Phenomenology of Turbulent Reacting Flows," Proceedings of the DOE Workshop on Modeling of Combustion in Practical Systems, Courtesy Associates, Washington, D. C., 1978.

3. Anderson, Paul R., LaRue, John C., and Libby, Paul A., "Turbulence Measurements of a Two-Dimensional Helium Jet in a Moving Airstream," Project SQUID Technical Report UCSD-9-PU, 1977.

RESEARCH ON TURBULENT MIXING

California Institute of Technology, Pasadena, California
Subcontract No. 8960-1

Professor A. Roshko, Principal Investigator
Prof. P. E. Dimotakis, Co-Investigator
Mr. Luis P. Bernal, Research Assistant
Mr. Daniel B. Lang, Research Assistant

Introduction

The objective of this research is to obtain a better understanding of the turbulent mixing processes that occur in mixing layers between gas streams of different velocities and densities. Such mixing layers are often a basic element in flows which occur in propulsive devices; examples of problems to which the research is relevant include turbulent combustion, jet noise, and thrust augmentation. The research has proceeded along two parallel lines. On the one hand, we have been making measurements of various statistical properties of the mixing region and their dependence on parameters such as Reynolds number, velocity ratio and density ratio. Such information provides important inputs for engineering models and calculation methods. On the other hand, we have been using the quantitative measurements, e. g., time- and space-resolved concentration measurements, together with flow visualization to identify and describe the physical processes occuring in such mixing regions. Better understanding of the physics is important for the development of more realistic computing models and also for suggesting how turbulent mixing might be controlled or modified.

Discussion

The main effort continues to be devoted to the question of how three dimensionality develops in plane mixing layers which, from previous work in this and other laboratories, are now known to be dominated by large vortices or rollers which have fairly good spanwise organization (Refs. 1, 2). In recent work under this contract

(Ref. 3), the presence of streamwise streaks was discovered on spark shadow or schlieren views taken normal to the plane of the mixing layer. An example of a schlieren picture is shown here in Figure 1 which shows simultaneous side and plane views of a mixing layer between streams of helium and nitrogen at velocities 752 and 227 cm/sec., respectively, at a pressure of 4 atm. In Ref. 3 it was suggested that these streaks mark the edges of streamwise vortices which are created by some kind of seconday instability on the main vortices, possibly of the Gortler or Taylor type. We are engaged in a series of experiments to further elucidate the nature of these secondary organized structures and to relate them to various parameters of the mixing layer. We believe that their appearance and subsequent development is an important link in the development of the three dimensionality and small scales that must be present in turbulent flow at high Reynolds number. They are also thought to be related, in some way, to the enhanced internal mixing which occurs above a certain Reynolds number, as found in Ref. 3.

On repeated pictures like that in Figure 1, it was noted that the streaks appeared to occur in more or less the same spanwise positions. This was confirmed by making long time exposures, an example of which is shown in Figure 2a for the same conditions as in Figure 1. Most of the recent work has been centered on studying these long-time exposure patterns and their changes with various parameters.

One question is whether the streaks originate from fixed disturbance points upstream in the settling chamber or in the boundary layers of the splitter plate, or whether their spacing is governed by an instability criterion. Accordingly, various changes were made in the screen configuration in the settling chamber, in the length of the splitter plate and in the trailing edge of the latter. Also disturbances in the nature of small vortex generators were deliberately introduced in the entrance flow. Secondly, the various parameters of the flow, in particular the Reynolds number, were varied. From all these we tentatively conclude that the mean pattern of the streaks is not tied to upstream disturbances but is determined by flow criteria. Some of the results on which we base this conclusion are the following.

1. The pattern of streaks depends on Reynolds number Re. When velocity and pressure are changed in such a way as to keep Re constant, the pattern remains unchanged. When Re is increased the pattern shifts upstream and the average spacing decreases, and conversely for decrease in Re. If we denote the position of the front of the pattern by x_f then the dependence on Reynolds number $Re = (U_1-U_2)(x_f-x_0) / \nu_{N_2}$ for various values of the velocity ratio U_2/U_1 is as shown in the following table, where x_0 is the effective origin of the shear layer and ν_{N_2} is the kinematic viscosity on the (lower speed) nitrogen side.

U_2/U_1	0.14	0.30	0.38	0.50
$10^{-4} Re$	3.9	3.6	3.1	1.5

2. The mean spacing of the streaks or bands scales with the momentum thickness of the initial, laminar shear layer approximately as $\lambda = 18\theta$. The adjustments in the spacing, when flow conditions are changed, is by appearance or disappearance of some of the bands and slight displacement of some of the others.

3. The spanwise positions, but not the mean spacing of the bands, could be altered by changing the screen configuration in the settling chamber.

Still another question concerns the relation of these patterns to the enhanced mixing which was noted in Ref. 3. In figure 2b the streamwise development of a mixedness parameter, which was measured in Ref. 3, is scaled to the flow picture in Figure 2a. From this it appears that the increase in mixedness occurs toward the downstream side of the streak pattern. Assuming that these streaks correspond to streamwise vortices, it may be conjectured that the enhanced mixing corresponds to some further instability or small scale breakdown of those vortices. In Ref. 3 it was also found that the enhanced mixedness was accompanied by an increase in power spectral content at high values of wave number. Those wave numbers are considerably higher than what would be inferred from the mean streak spacing, again suggesting a breakdown to smaller scales. New experiments designed to correlate various details of the fluctuating concentration field and the streak patterns are underway.

Notes and References

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2. Winant, C. D. Browand, F. K. 1974 Vortex pairing; the mechanism of turbulent mixing-layer growth at moderate Reynolds number. J. of Fluid Mechanics 63, 237-255.

3. Konrad, John Harrison 1976 An experimental investigation of mixing in two-dimensional turbulent shear flows with applications to diffusion-limited chemical reactions. Project SQUID Technical Report CIT-8-PU.

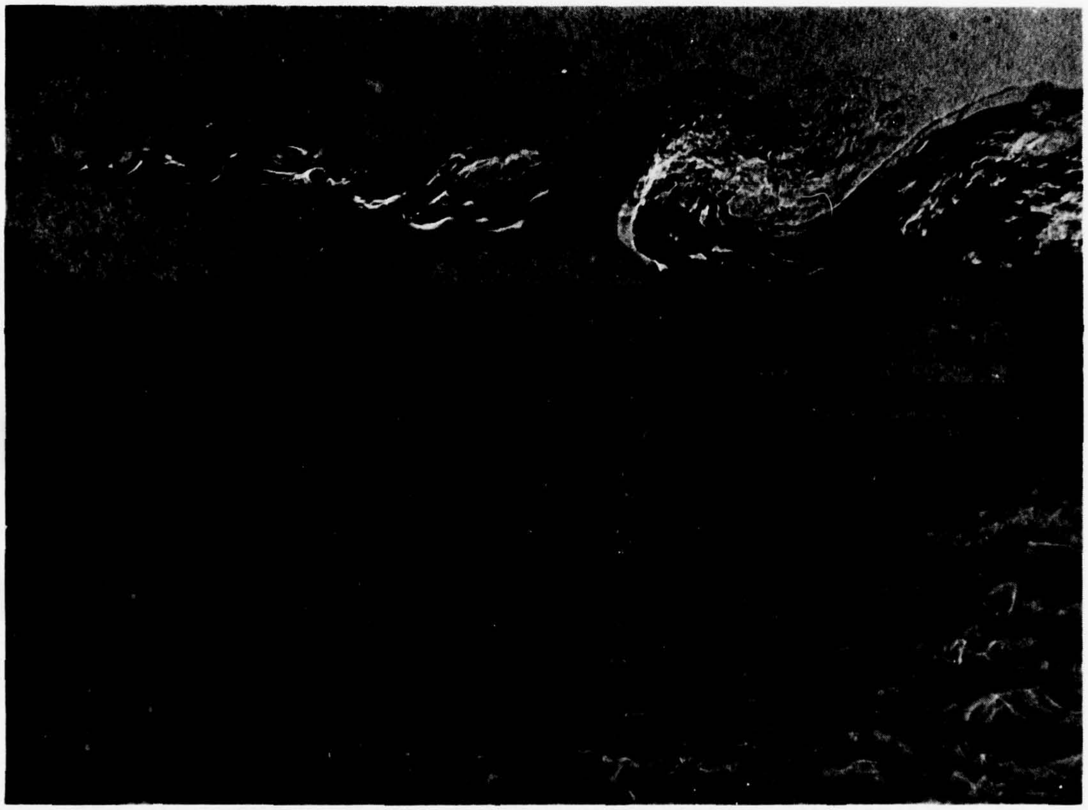
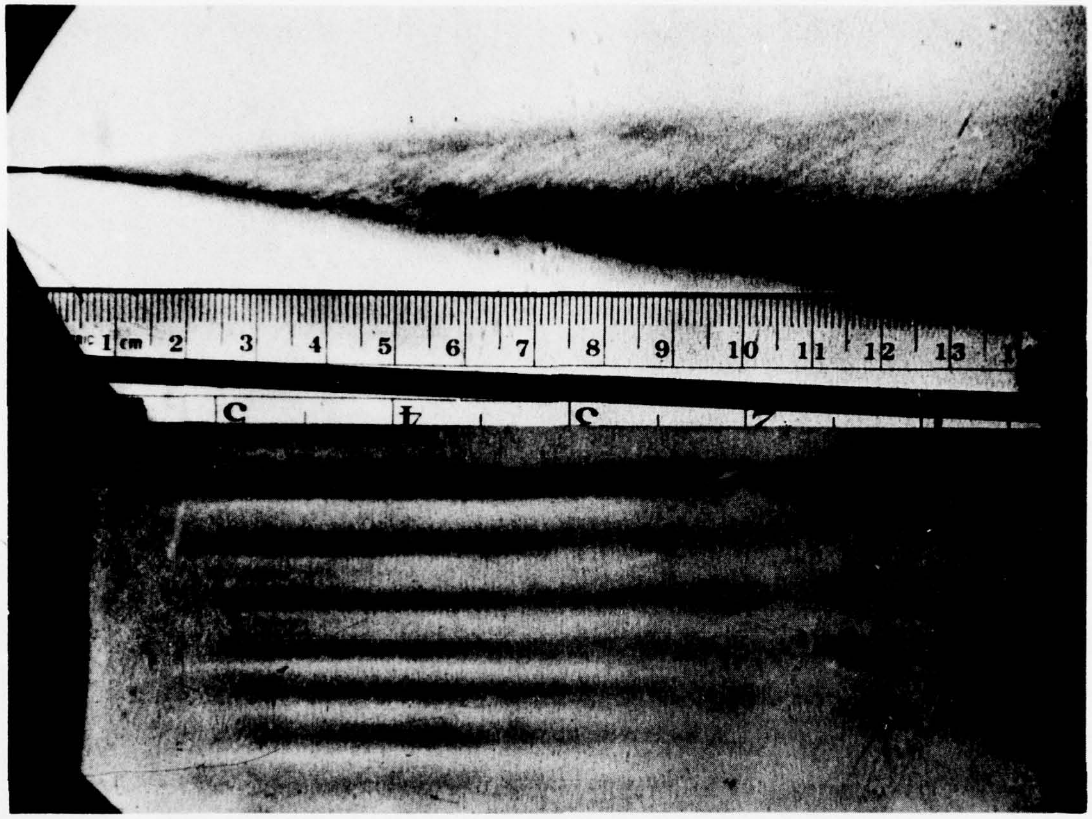
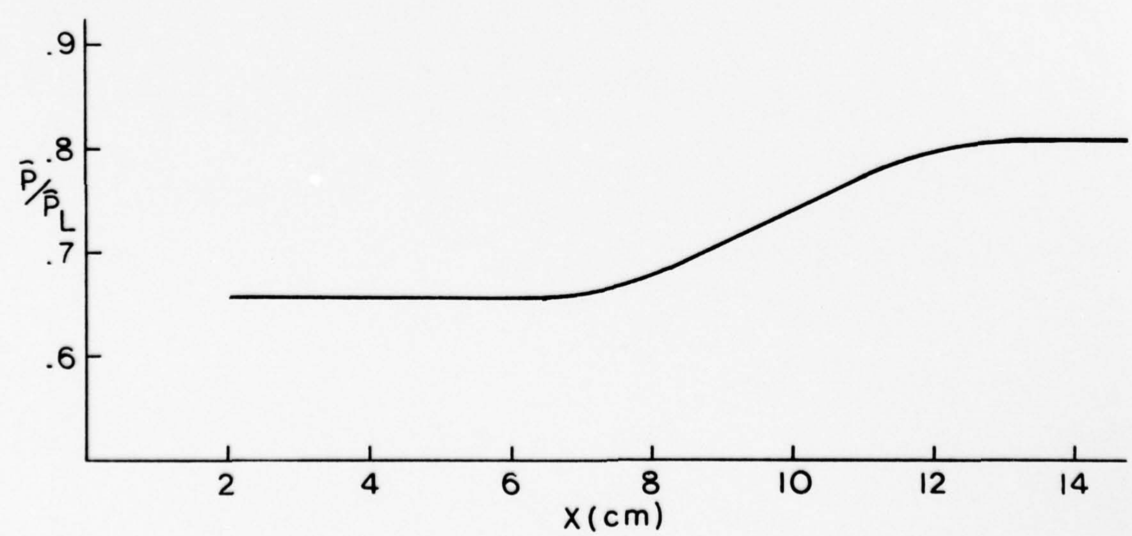


Figure 1



a



b

Figure 2

SWIRLING HEATED TURBULENT FLOWS
AS RELATED TO COMBUSTION CHAMBERS

University of Colorado, Boulder, Colorado

Professor M. S. Uberoi, Principal Investigator

Discussion

Role of axial flow in laminar and turbulent swirling flows. In an extensive theoretical investigation (Project SQUID Technical Report UC-1-PU, Mechanisms of Decay of Laminar and Turbulent Vortices, 1977) we have shown that the variation of axial flow plays a very important role in the development of swirling flows. We are investigating methods of calculating these axial flows in some swirling flows of practical interest. Our attention is first confined to the case of a potential vortex with a concentrated distribution of vorticity on the axis of the vortex.

Coherent structure and instabilities in the initial region of a plane turbulent air jet of variable initial temperature. Instabilities and coherent structure of isothermal and heated air jets are examined using shadowgraph, velocity and temperature probes in Reynolds number range 10^3 - 10^4 based on jet width. In the two mixing regions at the jet edges shadowgraphs show a very coherent structure of two symmetric spatially growing eddies, which engulf the whole jet and then break up to produce a turbulent jet. The distance required for the roll up of the vortex sheet or the development of eddies and their breakdown depends on the initial velocity profile of the jet. The spectra of velocity and temperature fluctuations at a point do not show a distinct frequency, there being considerable jitter, although a central frequency can be assigned to the spectra. Strouhal number based on the central frequency was measured as a function of jet Reynolds number. The roll up of the two vortex sheets at the jet edges into distinct eddies decreased as the influence of the buoyancy was increased by increasing initial jet temperature to 300^0C.

We are in the process of completing one phase of this work and are preparing a report for publication.

SECOND-ORDER CLOSURE MODELING
OF TURBULENT COMBUSTION

Aeronautical Research Associates of Princeton, Inc.
Princeton, New Jersey
Subcontract No. 8960-26

Ashok K. Varma, Principal Investigator
Coleman duP. Donaldson

Introduction

The interaction between turbulence and chemistry is of considerable importance in determining combustion efficiency and pollutant formation as well as other combustion characteristics in many combustion and propulsion systems. This research program is directed towards the study of the turbulence-chemistry interaction using a complete second-order closure approach.

A second-order closure procedure requires the development of closure models for the higher-order correlations that appear in the transport equations for the means and the second-order correlations. We have proposed a delta function "typical eddy" model for the joint probability density function for all the scalars. We believe that a new principle has been formulated which permits rational closures for turbulent mixing and turbulent reacting flows.

Discussion

Recently a major advance has been made in the procedure for the construction of delta function typical eddy models. In the past we have struggled with defining a criterion for selecting the proportions of the species in the mixed cells (α_3 in a two species model and

α_4 , α_5 and β_6 in a three species model). In the previous progress report (Ref. 1) we had proposed using the midrange value of the $\overline{s^3}$ moment to select α_3. However, we now believe that the following criterion should be used for determining the typical eddy structure.

Minimum Entropy of Mixing Principle. The free parameters in the delta function typical eddy model should be chosen to minimize the entropy of mixing.

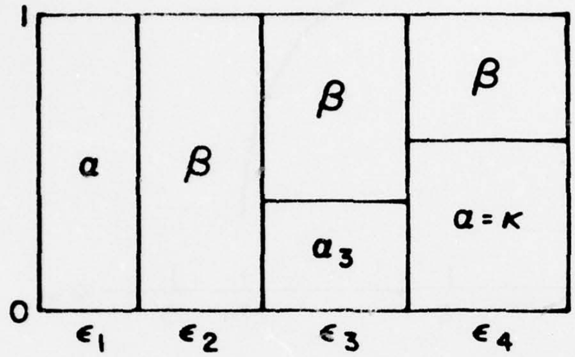
The transport equations for the means and various second-order correlations incorporate the entropy-increasing effects of molecular transport processes, and this is reflected in the values of the means and correlations at any given point in the flow. It is important that the modeling procedure not add any more entropy to the system, that is, there should be no entropy of modeling or entropy increase due to our ignorance. This can be accomplished by selecting the model structure, within the allowable range of parameters, that has the least entropy.

The notion can also be understood from the viewpoint of large eddy structures. Consider the mixing of two initially separate streams of inert gases α and β . The large eddies in a turbulent flow cause stretching and folding and intertwining of the streams, but do not cause an increase in the entropy of the system. The entropy of mixing reflects only the molecular mixing processes and therefore, selecting the minimum entropy model is consistent with the large structures viewpoint of turbulent flow.

For a two species model, the parameter α_3 is selected on the basis of minimum entropy. For a three species model, one has to simultaneously determine α_4 , α_5 and β_6 to minimize the entropy. In practice, this concept is very convenient to use and is working well. We have carried out tests on a two species model in the past month and some typical results are discussed below. In practice, the entropy appears to be a smoothly-varying function of the parameter α_3 and the selection of α_3 for minimum entropy is quite straightforward. A few examples of the minimum entropy "typical eddy" structures at various points in the statistically valid moment space are shown below.

The model structure is computed as a function of α_3 for specified values of the moments $\overline{\alpha}$, $\overline{\alpha^2}$, $\overline{s\alpha}$ and $\overline{s^2}$. In general, valid model structures ($\epsilon_i \geq 0$, $0 < \kappa < 1$) are obtained for a range of values of α_3 . The program calculates the total entropy of the structures and selects the value of α_3 for minimum entropy.

Model Structure



$$s = \frac{\rho}{W_\beta \, \bar{p} / R\bar{\bar{T}}}$$

$$\Delta = 1 - W_\beta / W_\alpha$$

$$W_\alpha = 32$$

$$W_\beta = 2$$

$$\text{Total Entropy} = \sum_i \epsilon_i \left[\rho_i \alpha_i \left(c_{v_\alpha} \ln T_i - \frac{R}{W_\alpha} \ln \rho_i \alpha_i \right) + \rho_i \beta_i \left(c_{v_\beta} \ln T_i - \frac{R}{W_\beta} \ln \rho_i \beta_i \right) \right]$$

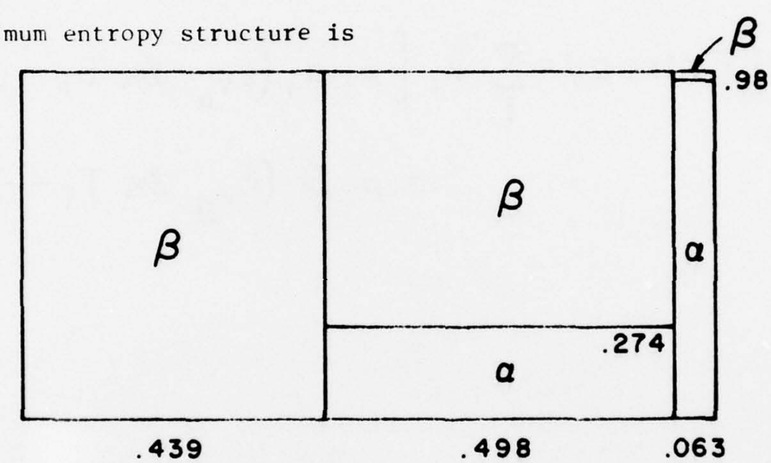
Example 1

Consider the point in moment space.

$\bar{\alpha}$	$\overline{\alpha^2}$	$\overline{s\alpha}$	$\overline{s^2}$
0.2	0.1	1.0	12.0

The valid range of α_3 is 0.12 to 0.27. The total entropy of the structure as a function of α_3 is sketched below.

The minimum entropy structure is

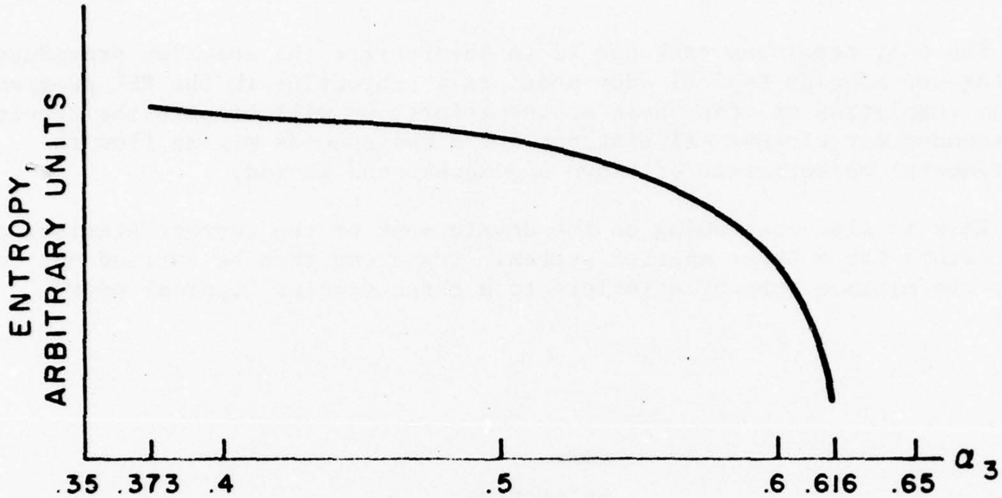


Example 2

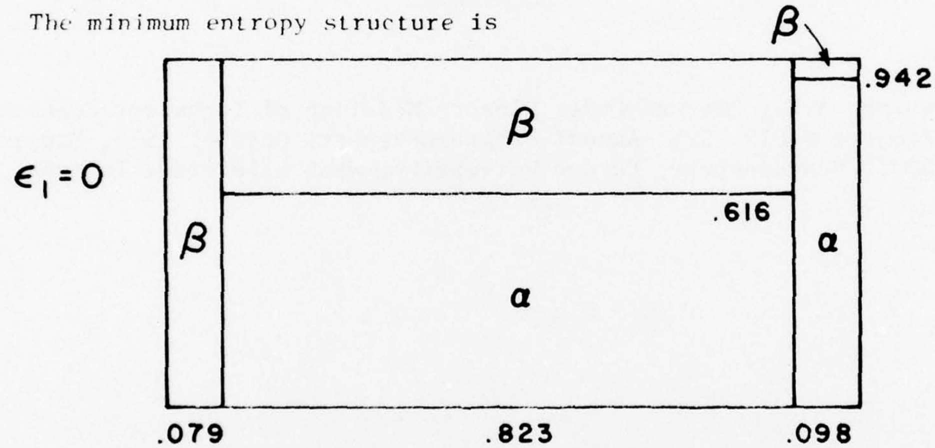
Consider the point

$\overline{a}$	$\overline{a^2}$	$\overline{sa}$	$\overline{s^2}$
0.6	0.4	2.0	12.0

The valid range of α_3 is 0.37 to 0.61. The variation of entropy vs. α_3 is sketched below.



The minimum entropy structure is



Further tests are continuing to ascertain whether the minimum entropy structure is <u>always</u> a three cell structure as was the case in the above two examples, and if this were so, to attempt to formulate even simpler rules to determine the structure.

We have also made progress in other areas of our effort.

<u>Second-Order Closure Program Development</u>

The second-order closure program including the density correlation equations is now operational. The equations for $\overline{\rho'\alpha'}$, $\overline{\rho'\beta'}$ and $\overline{\rho'\gamma'}$ are solved in pass 11 and the equations for $\overline{\rho'h'}$ and $\overline{\rho'\rho'}$ are solved in sequence in pass 12 of the RSL computer program.

The only remaining task now is to incorporate the solution procedure for the two species typical eddy model as a subroutine to the RSL program. On the completion of this phase of the effort, we will compare the results of second-order closure calculations for a two species mixing flow to experimental measurements of Brown and Roshko and Konrad.

Work is also continuing on the development of the correct statistical constraints for a three species system. Tests can then be carried out to apply the minimum entropy principle to a three species "typical eddy" model.

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V. INDEX BY CONTRACTOR

INDEX BY CONTRACTOR

Page

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

YALE UNIVERSITY

APPENDIX A

TECHNICAL REPORTS

SQUID TECHNICAL REPORTS ISSUED SINCE 1 OCTOBER 1978

SQUID NUMBER	TITLE AND AUTHOR(S)	ADA NUMBER
CSU-1-PU	Visualization Study of Vorticity Amplification in Stagnation Flow by Willy Z. Sadeh, Herbert J. Brauer and James A. Garrison. October 1977.	ADA048629
UC-1-PU	Mechanisms of Decay of Laminar and Turbulent Vortices by M. S. Uberoi, November 1977.	ADA049176
SU-2-PU	An Optical Particle-Sizing Counter for In-Situ Measurements by Don Holve and Sidney Self, January 1978.	ADA050757
PIB-35-PU	Application of the Integrated Raman and LDV System by L. Lederman and A. Celentano, February 1978.	in process

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER 6	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Project SQUID · Semi-Annual Progress Report. April 1978 9 1 Oct 77-31 Mar 78	5. TYPE OF REPORT & PERIOD COVERED Progress Report-Semi-Annual 10-1-77 to 3/31/78
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 T. Adamson, F. Carta, A. Dean, J. Foss, F. Browand, R. Chang, A. Eckbreth, F. Gessner, E. Bruce, N. Chigier, J. Fenn, J. Johnston, M. Lapp, W. O'Brien, W. Sadeh, A. Varma, S. Lederman, A. Roshko, R. Simpson, P. Libby, J. Ross, M. Uberoi	8. CONTRACT OR GRANT NUMBER(s) 15 N00014-75-C-1143 NR-098-038
~~9. PERFORMING ORGANIZATION NAME AND ADDRESS~~	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Power Program, Code 473 Department of the Navy, 800 No. Quincy Street Arlington, Virginia 22217	12. ~~REPORT DATE~~ 11 1 April 1978
	13. ~~NUMBER OF PAGES~~ 100
~~14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)~~ 9. Performing Organization Project SQUID Headquarters, Purdue University Chaffee Hall, West Lafayette, Indiana 47907	15. SECURITY CLASS. (of this report) 12 93p. Unclassified
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Semi-Annual
Aerodynamics and Turbomachinery
Combustion and Chemical Kinetics
Measurements
Turbulence

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Reports of progress during the past six months on the 22 research programs comprising Project SQUID are presented. The research programs fall into the areas of Aerodynamics and Turbomachinery, Combustion and Chemical Kinetics, Measurements and Turbulence. Project SQUID is a cooperative program of basic research related to jet propulsion. It is administered by Purdue University and sponsored by the Office of Naval Research.

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